COMPARISONS OF THREE OPTICAL DENSITY PSEUDOCOLOR ENCODING METHODS

by

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Abstract

Three optical density pseudocolor encoding methods are studied and their results are presented with discussions. The characteristics of each method are investigated and comparisons are made among them.

The first method involves the use of the scattered light of the developed silver grains on the object film while the second method requires a modulation of the input image with clear lines and spatial filtering. Both methods are unsatisfactary in the color quality.

The third method is based on the phase modulation of the input image, and it combines the second method with a bleaching process. This method produces very colorful results, but there is one major disadvantage that one color of the output image may correspond to two gray levels, so there exists a risk of confusing different gray levels.

In conclusion, we say that the third method is the most potential one of the three methods, particularly in the encoding of high contrast pictures. The high sensitivity of this method can facilitate the differentiation of small change in density which is difficult to discriminate by eye.

Chapter 1

Introduction

Density pseudocolor encoding is a technique for introducing false colors into a black and white film, such that different colors correspond to different gray levels. Since human eye has better ability to distinguish different colors than gray levels, a color encoded image can often facilitate the interpretation and provide better visual discrimination.

Historically, the use of pseudocolor encoding filters in an imaging system was first introduced by Rheinberg[1] in 1896, who reported the application of color filtering in microscopy. Recently, many methods have been proposed using either optical or computer techniques. In this research we concentrate our interest in three optical methods of the density pseudocolor encoding.

The density pseudocolor encoding method was first reported in 1976 by Liu and Goodman,[2] based on nonlinear filtering with half-tone screens. Indebetouw[3] combined this technique with theta modulation to encode each density slice independently. An encoding method of addition of an incoherent image and a coherent reversed image, each of them with a different color, was proposed in 1979 by Santamaria et al.[4], and the method gives much better resolution than the above two methods. Another method based on the addition of a positive and and a negative images has been proposed by Chao et al.[5] where the two images are color encoded through modulation by a Ronchi grating and color filtering. Guel et al.[6] have also reported a two primary color system with an image hologram in which the noise of low frequency filtering is avoided.

Later on, a pseudocolor technique based on the generation of contrast reversed image have been developed by Rodrignez et al.[7]. In 1982, Arizaga et al.[8] have proposed a two primary color method using the light scattered from film grains under oblique illumination. Crousson et al.[9] have presented a pseudocolor system for one-dimensional objects, based on the diffraction characteristics of phase gratings registered on photorefractive crystal plates. More recently, a technique of density pseudocolor encoding with three primary colors using white light optical processor has been realized by F.T.S.Yu et al.[10].

Some of the above methods require the use of coherent light sources, while others use white light sources only. However, we emphasize here those methods of white light optical processing. The major advantages of it, as in contrast with the coherent counterpart, are the simplicity, versatility, low cost and artifact noise immunity.

Most of the above methods are tried out in different laboratories by different research groups, and the object films used are not the same. For discussion and, in particular, for comparison of the results of those methods, we studied three methods using the same object films and, in this way, we hope to be able to draw a more objective and unbiased conclusion.

The first method[8,11,12] uses the scattered light by the developed silver grains of the film to produce the contrast reversed image, and spatial filtering is unnecessary. The second method[7,13] requires a modulation of the input image with clear lines and spatial filtering is needed. The third method[14] is based on the phase modulation of the input image, and it combines the second method with a bleaching process.

In this thesis, we first explain the principles of the three methods in Chapter 2, where we shall derive the theories of the second and the third methods independently. Later on, the experimental set-up and the procedures are described in Chapter 3. Finally, the pseudocolor encoding results and discussions will be presented in Chapter 4.

Chaphter 2

Theory

2.1 Definitions of the transmittances of a film

The intensity transmittance of a black and white film is defined as

$$T_i(x,y) = I_o(x,y) \;/\; I_i(x,y), \qquad (2.1.1)$$

where $I_i(x,y)$ and $I_o(x,y)$ denote the input and output irradiances.

The amplitude transmittance of a black and white film is defined as

$$T_a(x,y) = E_o(x,y) \;/\; E_i(x,y), \qquad (2.1.2)$$

where $E_i(x,y)$ and $E_o(x,y)$ denote the input and output amplitude of light. It should be noted that $T_a(x,y)$ can be complex. Obviously, we can see the relation that

$$T_i(x,y) = |\,T_a(x,y)\,|^2. \qquad (2.1.3)$$

The photographic density D is defined as

$$D(x,y) = -\log T_i(x,y). \qquad (2.1.4)$$

2.2 Principle of Method 1 - method by light scattering by developed silver grains in the film

The pseudocolored image of this method is obtained by the simultaneous addition of a direct contrast image and a contrast reversed image, each in a different color.

The direct contrast image is obtained by the direct transmission through the object film, while the contrast reversed image is obtained by using the light scattered from the developed silver grains of the original film under oblique illumination.

When the incident light illuminates the film perpendicularly as in Fig. 2-1, the direct transmitted light will be inversely proportional to the density of the silver grains of the film, thus a direct contrast image of the film can be produced by the direct transmitted light.

However, when the incident light illuminates the film obliquely as in Fig. 2-2, part of the light will be scattered by the silver grains along random directions. As the density of those grains increases, the scattered light will increase. Then, an approximate contrast reversed image can be obtained either by the diffuse reflected light or by the diffuse transmitted light.

In Fig. 2-3a and 2-3b, the collimated light beam from the light source S1 illumates the film F perpendicularly to produce a direct contrast image at plane I. At the same time, the film F is illuminated from behind by diffuse transmission

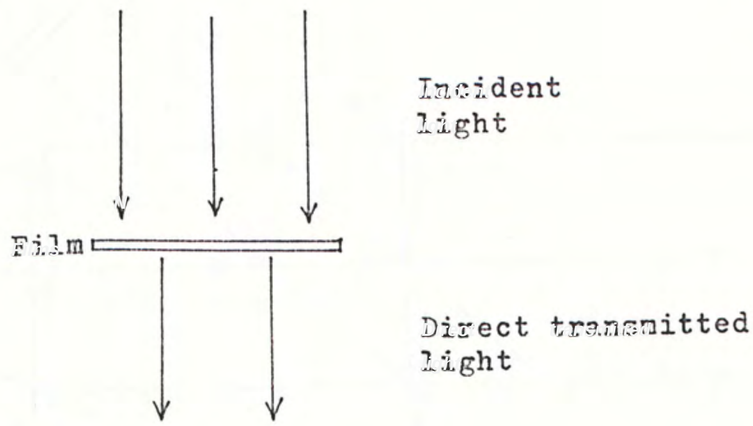

Fig. 2-1 Diagram of direct transmission.

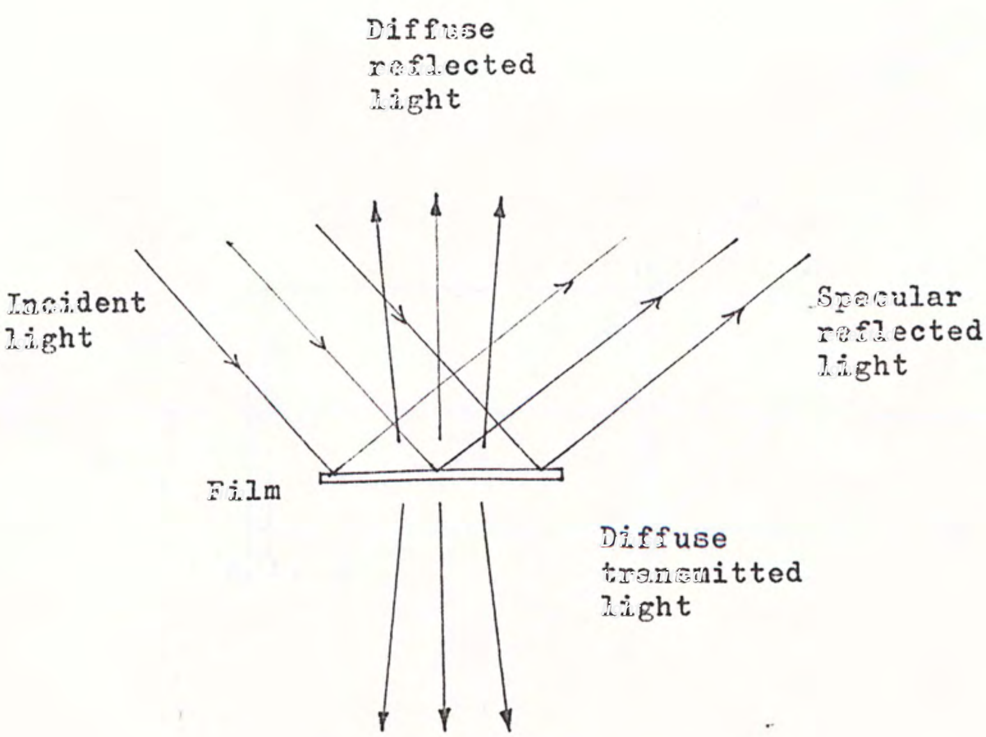

Fig. 2-2 Diagram of diffuse transmission
and diffuse reflection.

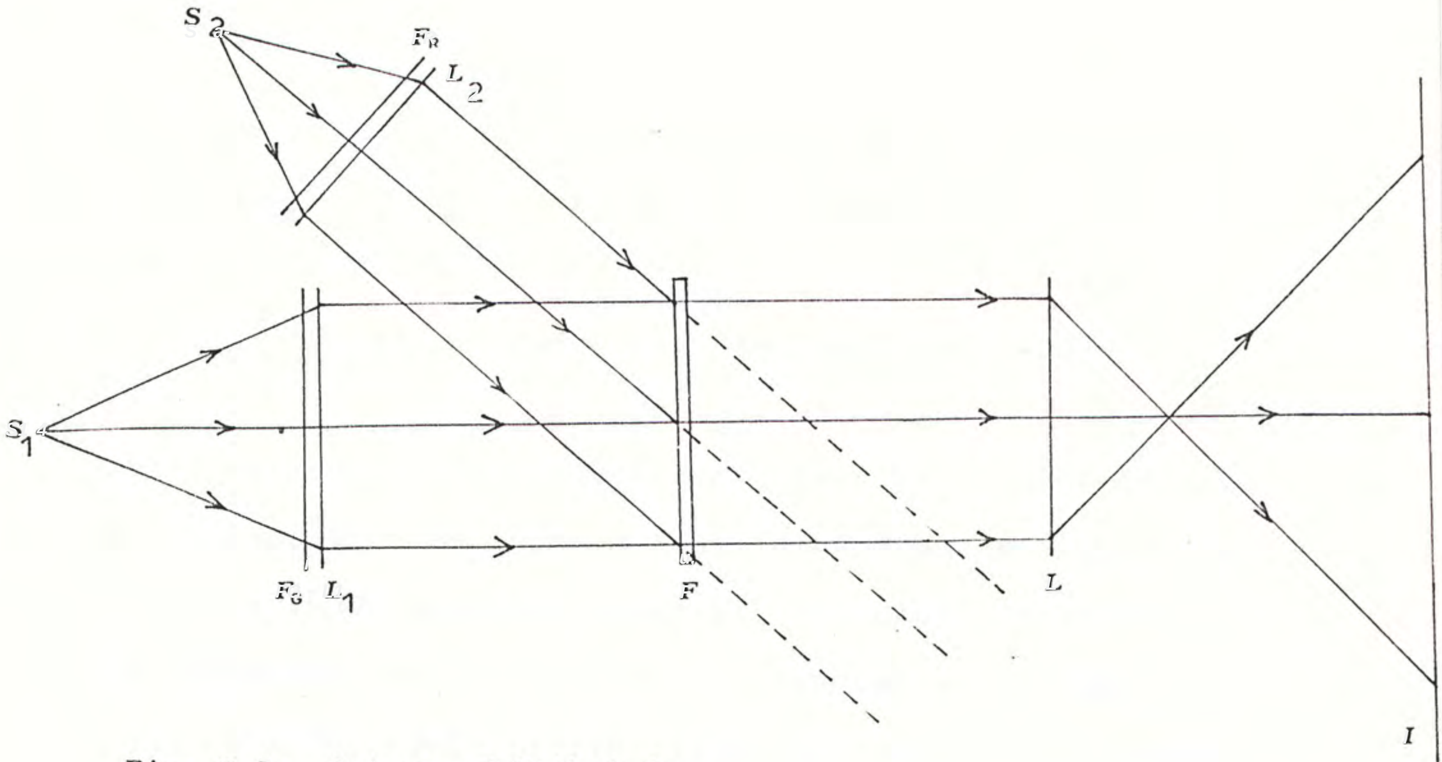

Fig. 2-3a Set-up of Method 1A.

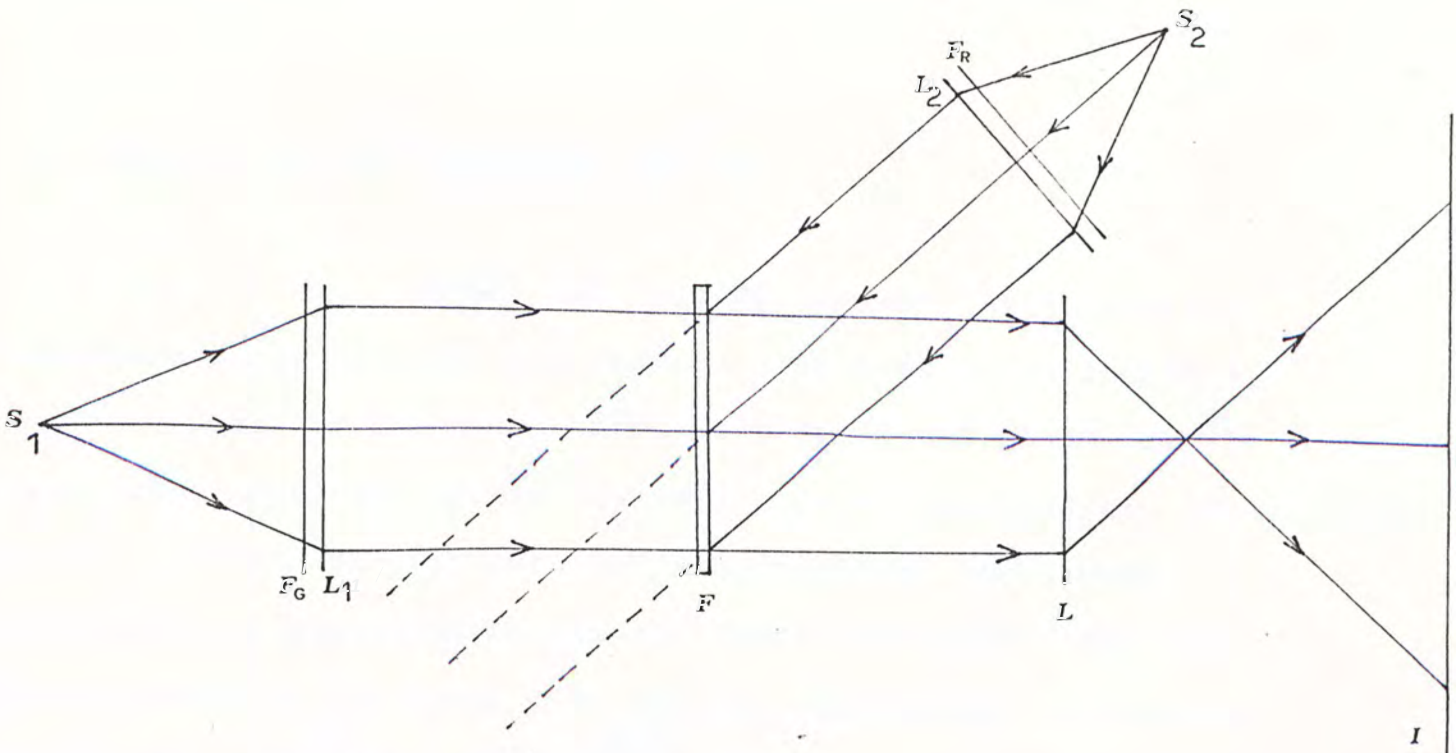

Fig. 2-3b Set-up of Method 1B.

L_1 and L_2 are collimating lens; F_G and F_R are green and red filters respectively; L is a projecting lens.

or from the front by diffuse reflection as in the figures respectively, and an approximate contrast reversed image is obtained at the plane I. With two color filters placed in front of S1 and S2, a pseudocolored image is produced at plane I.

The method with the contrast reversal achieved by diffuse transmission as in Fig. 2-3a is denoted as Method 1A, while the method with the contrast reversal achieved by diffuse reflection as in Fig. 2-3b is denoted as Method 1B.

But the contrast reversal does not hold for the whole range of density of the silver developed grains. Saturation effect takes place at the higher densities. This effect will be described in Chapter 4 - the results and discussions.

2.3 The 4 f spatial filtering system

It is well known that optical lenses have Fourier transform property. Fig. 2-4 shows a lens L of focal length f and its focal planes are denoted as plane 1 and plane 2. A film with amplitude transmittance $T(x,y)$ is inserted at the plane 1 while uniform parallel monochromatic light beam of wavelength λ illuminates from the front. The light amplitude distribution at the plane 2 is exactly the Fourier transform of $T(x,y)$ apart from a constant phase factor.

Let $E(x',y',\lambda)$ denote the light amplitude distribution for a given wavelength λ at the plane 2, then we have the

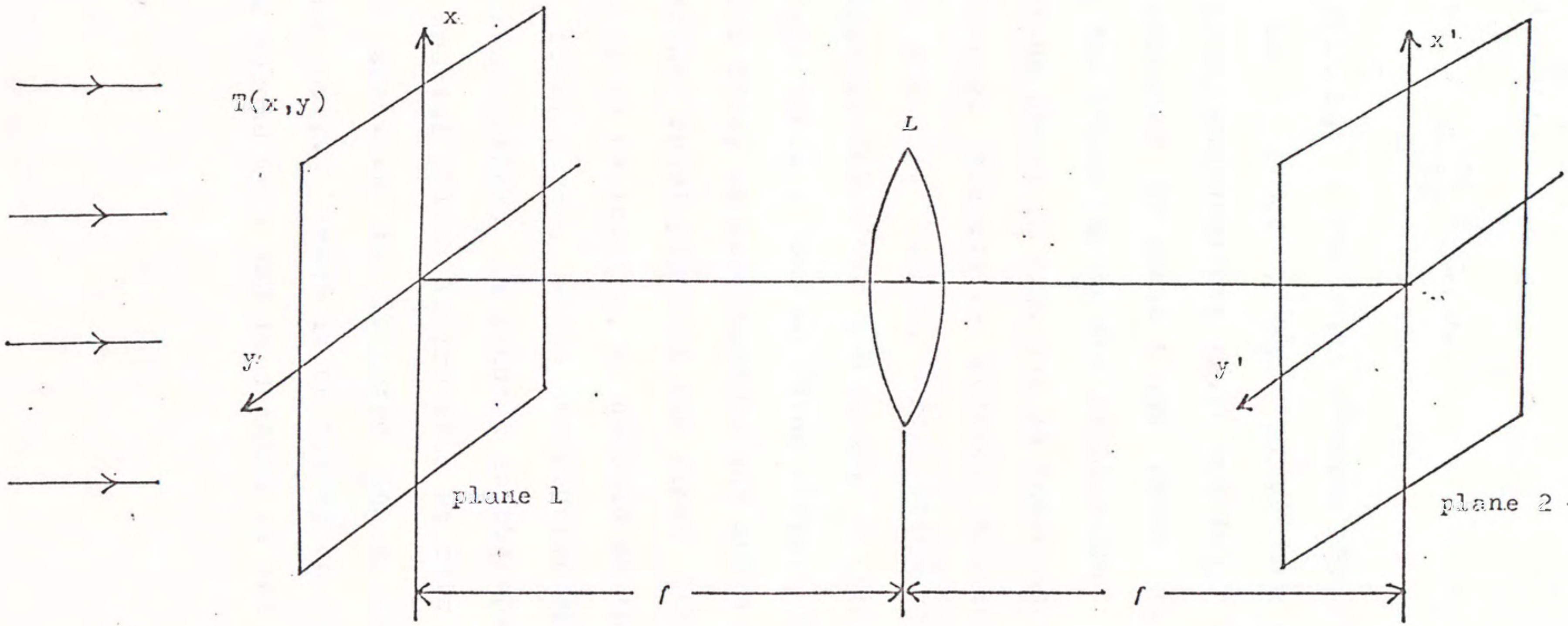

Fig. 2-4 Geometry for the determination of the optical Fourier transformation.

following equation,

$$E(x',y',\lambda) = \frac{e^{ikf}}{if\lambda}\,\bar{T}(\omega_x,\omega_y), \qquad (2.3.1)$$

where $\bar{T}(\omega_x,\omega_y)$ is the corresponding Fourier transform of $T(x,y)$; $\omega_x = x/\lambda f$, $\omega_y = y/\lambda f$ are the respective spatial frequency coordinates; (x,y) and (x',y') are the linear spatial coordinates at plane 1 and plane 2. However, we usually drop the phase factor for simplicity.

The set-up shown in Fig. 2-5 is known as the 4 f spatial filtering system. Successive Fourier transformations are achieved by the two lenses. For pseudocolor encoding involving spatial filtering operation, a film obtained from the object film through some encoding steps, which is known as the encoded film, is processed in the above system.

The front focal plane of the first lens, where the encoded film is to be located, is denoted as the input plane. The middle focal plane, where the Fourier spectrum of the encoded film is formed, is denoted as the spatial frequency plane. The spatial filter is inserted at this plane, so that the spatial spectrum is filtered in a desired manner. Finally, the output image is be formed on the back focal plane of the second lens and is denoted as the output plane.

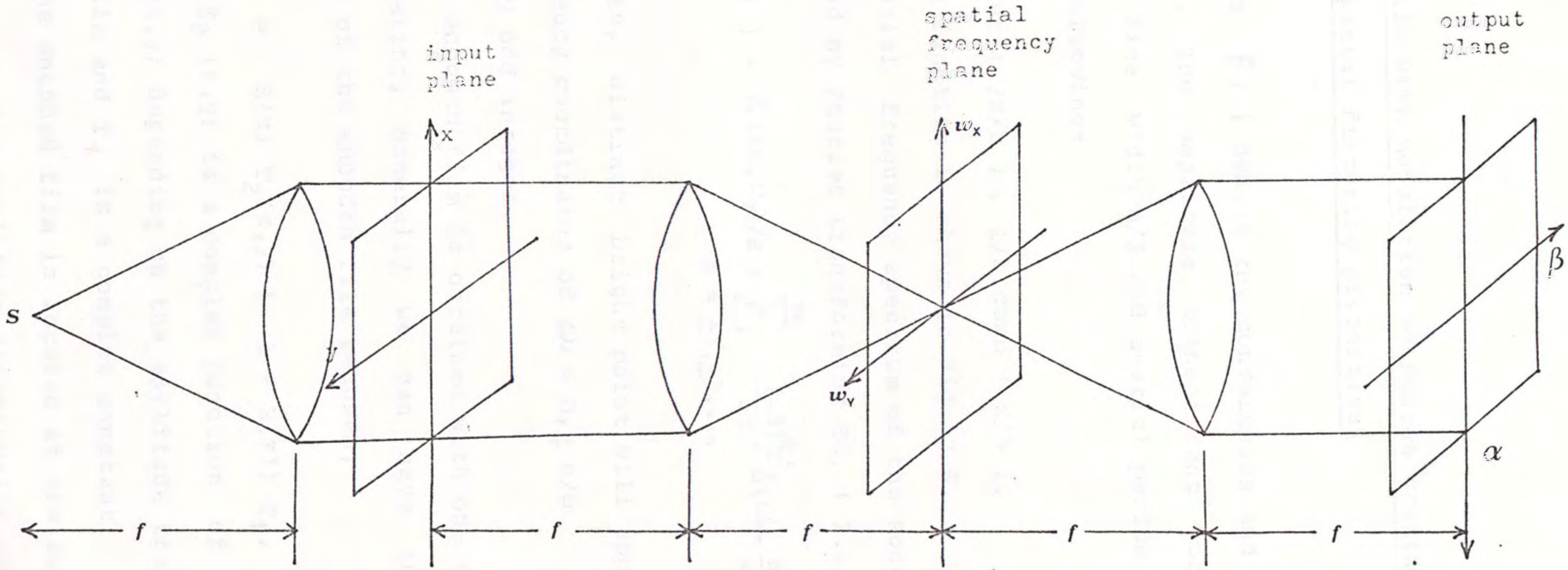

Fig. 2-5 4 f spatial filtering system.

2.4 Encoded film with modulation by Ronchi grating and its spatial filtering properties

Let * and $\mathbf{F}[\ ]$ denote the convolution and the Fourier transformation. The amplitude transmittance of a Ronchi grating with line width b/2 and spatial period b can be expressed as following:

$$R(x) = \mathrm{rect}(\ 2x/b\ ) * 1/b\ \mathrm{comb}\ (\ x/b\ ), \qquad (\ 2.4.1\ )$$

and this function is shown in Fig. 2-6.

The spatial frequency spectrum of the Ronchi grating can be obtained by Fourier transforming Eq. (2.4.1):

$$\mathbf{F}[\ R(x)\ ] = \delta(\omega_x, \omega_y)/2 + \sum_{n=\pm 1, \pm 3, \ldots}^{\infty} \frac{(-1)^{\frac{n-1}{2}}}{n\pi} \delta(\omega_x - \frac{n}{b}, \omega_y) \ . \qquad (\ 2.4.2\ )$$

Obviously, distinct bright point will appear at the spatial frequency coordinates of $\omega_x = 0, \pm\ n/b$ and $\omega_y = 0$ where n is any odd integer.

When an encoded film is obtained with one modulation by a Ronchi grating, generally we can have the amplitude transmittance of the encoded film becomes,

$$T(x,y) = R(x)\ T_2(x,y) + (1 - R(x))\ T_1, \qquad (\ 2.4.3\ )$$

where $T_2(x,y)$ is a complex function of the spatial coordinates (x,y) depending on the amplitude transmittance of the object film and T_1 is a complex constant.

When the encoded film is located at the output plane of the 4 f system, the amplitude distribution on the spatial

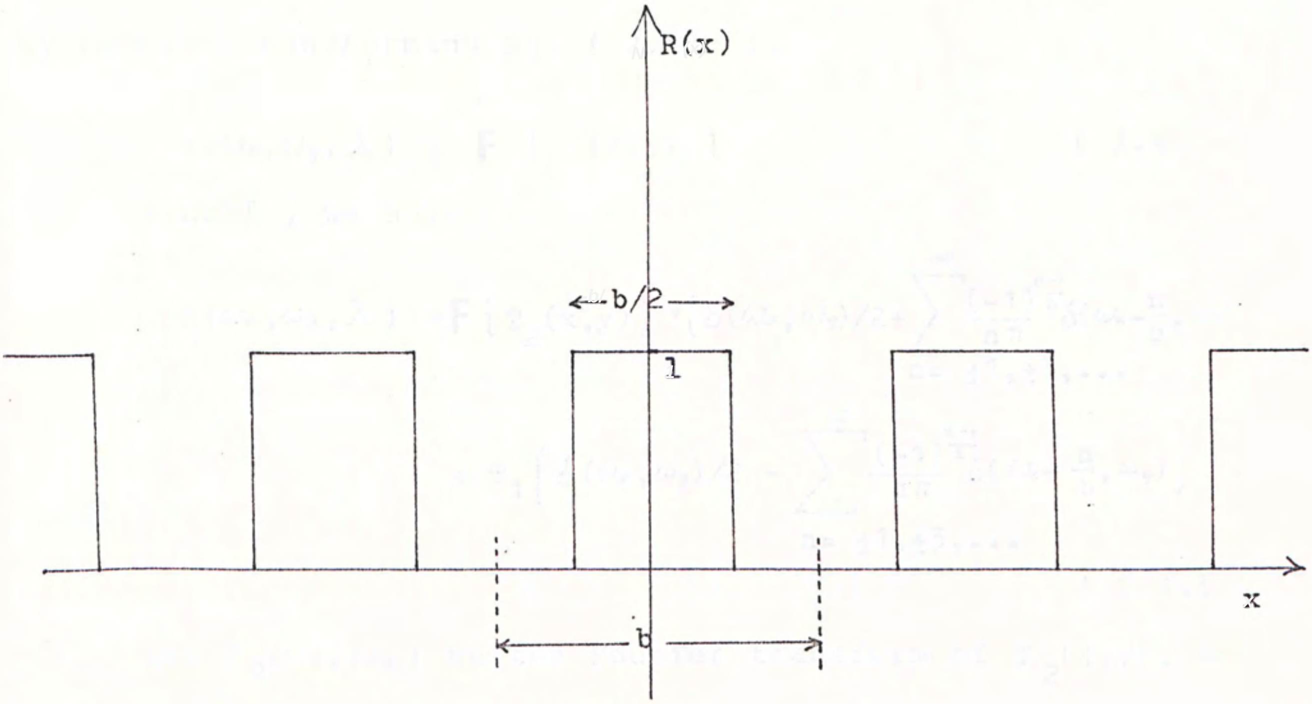

Fig. 2-6 Graph of function R(x).

frequency plane for a given wavelength λ will be obtained by Fourier transforming Eq. (2.4.3).

$$E(\omega_x,\omega_y,\lambda) = \mathbf{F}\,[\,T(x,y)\,] \qquad (2.4.4)$$

Finally, we have

$$E(\omega_x,\omega_y,\lambda) = \mathbf{F}\left[T_2(x,y)\right] * \left[\delta(\omega_x,\omega_y)/2 + \sum_{n=\pm1,\pm3,\ldots}^{\infty} \frac{(-1)^{\frac{n-1}{2}}}{n\pi}\delta(\omega_x-\frac{n}{b},\omega_y)\right]$$
$$+ T_1\left[\delta(\omega_x,\omega_y)/2 - \sum_{n=\pm1,\pm3,\ldots}^{\infty} \frac{(-1)^{\frac{n-1}{2}}}{n\pi}\delta(\omega_x-\frac{n}{b},\omega_y)\right]. \qquad (2.4.5)$$

Let $\bar{T}_2(\omega_x,\omega_y)$ be the Fourier transform of $T_2(x,y)$, and by further simplification, we get

$$E(\omega_x,\omega_y,\lambda) = \left[\bar{T}_2(\omega_x,\omega_y) + \delta(\omega_x,\omega_y)/2\right]$$
$$+ \sum_{n=+1,+3,\ldots}^{\infty} \frac{(-1)^{\frac{n-1}{2}}}{n\pi}\left[\bar{T}_2(\omega_x-\frac{n}{b},\omega_y) - T_1\,(\omega_x-\frac{n}{b},\omega_y)\right] \qquad (2.4.6)$$

If there exists $\overline{\omega}_x$ such that $\bar{T}_2(\omega_x,\omega_y) = 0$ when $\omega_x \geqslant \overline{\omega}_x$, and $\overline{\omega}_x$ is small enough that $\overline{\omega}_x \leqslant 2/b$, then the whole spatial frequency spectrum can be spatially seperated into distinct spectrum orders with centers at $\omega_x = 0, + n/b$ and $\omega_y = 0$, where n is any odd integer.

The zero order amplitude distribution becomes

$$E_0(\omega_x,\omega_y,\lambda) = \bar{T}_2(\omega_x,\omega_y)/2 + T_1\delta(\omega_x,\omega_y)/2. \qquad (2.4.7)$$

The n-th order amplitude distribution becomes·

$$E_n(\omega_x,\omega_y,\lambda) = \frac{(-1)^{\frac{n-1}{2}}}{n\pi}\left[T_2(\omega_x-\frac{n}{b},\omega_y) - T_1\,\delta(\omega_x-\frac{n}{b},\omega_y)\right] ,$$

where n is any odd integer (2.4.8)

Inverse Fourier transforming Eq. (2.4.7) yields

$$\mathbf{F}^{-1}[\ E_o(\omega_x,\omega_y,\lambda)\ ] = (\ T_2(x,y) + T_1\ )/2 \qquad (2.4.9)$$

for the amplitude distribution in the output plane from the zero order. The output irradiance from the zero order is given by the modulus squared of Eq. (2.4.9).

$$I_{o\,\mathrm{OUT}} = \left|\ T_2(x,y) + T_1\right|^2/4 \qquad (2.4.10)$$

Similarly, inverse Fourier transforming Eq. (2.4.8) yields

$$\mathbf{F}^{-1}[\ E_n(\omega_x,\omega_y,\lambda)\ ] = \frac{(-1)^{\frac{n-1}{2}}}{n\pi}e^{\frac{inx}{b}}\left[\ T_2(x,y) - T_1\right]$$

(2.4.11)

for the amplitude distribution at the output plane from the n-th order. The output irradiance from the n-th order is given by the modulus squared of Eq. (2.4.11):

$$I_{n\,\mathrm{OUT}} = \left|\ T_2(x,y) - T_1\right|^2/n^2\pi^2, \qquad (2.4.12)$$

where n is any odd integer.

2.5 Principle of Method 2 - method by sampling by clear lines

Similar to Method 1, the pseudocolored image of this method is obtained by the superposition of a direct contrast image and a contrast reversed image, each in a different color. However, the direct contrast image is obtained from the zero order output image of the encoded film while the contrast reversed image is obtained from the first order image.

In this method, an object film F(x,y) is sampled by clear lines, so the encoded film can be expressed as Eq. (2.4.3) with $T_2(x,y) = F(x,y)$ and $T_1 = 1$.

$$T(x,y) = R(x)\,F(x,y) + (1 - R(x)) \qquad (2.5.1)$$

Then the output irradiance from the zero order becomes

$$I_{0\,OUT} = (1 + F(x,y))^2/4, \qquad (2.5.2)$$

and the output irradiance from the first order becomes

$$I_{1\,OUT} = (1 - F(x,y))^2/\pi^2, \qquad (2.5.3)$$

Since contrast reversal corresponds mathematically to the subtraction of the amplitude transmittance from a constant, it is obvious, from Eqs. (2.5.2) and (2.5.3), that the output images of the zero order and the first order have opposite contrast.

With the zero order spectrum and the first order spectrum filtered through different color filters, while other spectrum orders are blocked, a pseudocolored image can be obtained at the output plane.

2.6 Principle of Method 3 -method by phase modulation

The density distribution of the object film is denoted as $D_i(x,y)$. A modulated film with Ronchi grating is obtained by a single exposure, then the film is bleached in a suitable bleaching agent, such that the change of the optical path length of the bleached film Δd is proportional to the change of the density of the original film ΔD,

$$\Delta d = C \Delta D, \qquad (2.6.1)$$

where C is the bleaching constant.

The amplitude transmittance of the bleached film can be obtained by substituting $T_1 = e^{i\phi_1}$ and $T_2 = e^{i\phi_2(x,y)}$ into Eq. (2.4.3):

$$T(x,y) = R(x)\, e^{i\phi_2(x,y)} + (1 - R(x))\, e^{i\phi_1}, \qquad (2.6.2)$$

$$\text{where} \quad \phi_2(x,y) = \frac{2\pi C}{\lambda}\left(D_1 - \gamma D_i(x,y) \right) + \phi_o ;$$

$$\phi_1 = \frac{2\pi C}{\lambda} D_o + \phi_o .$$

D_1 is a constant related to the exposure; γ is the contrast coefficient of the film; D_o is the background density of the film, and ϕ_o is the phase shift introduced by the base of the film.

If white light source is used in the 4 f system, the spectral radiant intensity at wavelength λ is $A(\lambda)$, the output irradiance at wavelength from the zero order is obtained from Eq. (2.4.10).

$$I_{0\,\mathrm{OUT}} = A(\lambda) \left| e^{i\phi_2} + e^{i\phi_1} \right|^2 / 4 \qquad (2.6.3)$$

Further simplification gives

$$I_{0\,\mathrm{OUT}} = A(\lambda) \left(1 + \cos \Delta\phi \right)/2, \qquad (2.6.4)$$

where $\Delta\phi = \frac{2\pi}{\lambda} C(D_1 - D_0 - \gamma D_i(x,y))$.

On the other hand, the output irradiance from the first order becomes

$$I_{1\,\mathrm{OUT}} = A(\lambda) \left(1 - \cos \Delta\phi \right)/\pi^2. \qquad (2.6.5)$$

Eqs. (2.6.4) and (2.6.5) show that the density D_i of the object film is related to the irradiance of the output image from the zero or the first order at a certain wavelength λ. Thus the color of the output image is also related to the density of the object film. The pseudocolored image can be obtained at the output plane in either the zero order spectrum or the first order spectrum independently.

Chapter 3

Experimental Method

At first, an object film should be prepared for the density pseudocolor encoding. Two object films as following were chosen for the study :

1. A Kodak photographic step (tablet no.2, CAT 152 3398) which is a black and white gray scale film.
2. A dental X-ray film of teeth.

The pseudocolor encoding methods generally involve the following two steps: making an encoded film from the object film and using the encoded film to reconstruct a pseudocolored image. These steps are denoted as the encoding process and the reconstruction process.

3.1 The Encoding Process

3.1.1 Encoding process of Method 1

NO encoding process is necessary in Method 1 provided that the developed silver grains in the original black-and-white object film can scatter light. We found that some types of X-ray films do not scatter light satisfactorily. In that case, a copy of the original by either contact printing or enlarging was made on another film such as Kodak TP 2415 or

ILFORD FP4. These types of film were experimentally found to scatter light very well. Then, the copy film was used in the next step.

In our experiment, Kodak TP 2415 was used for copying the second object film which is a dental X-ray film, and the conditions of development and fixing are shown in Table. (1).

3.1.2 Encoding process of Method 2

The encoding was achieved by using a photographic enlarger setup shown in Fig. 3-1. The image of the original object film was projected upon a photographic plate or film, on top of which and in close contact was a 20 lines/mm Ronchi grating. After the usual development and fixing process, the encoded film was made.

The image on the encoded film is the superposition of the negative image of the object film and the Ronchi grating. This procedure is usually called the modulation of the object film by a Ronchi grating.

The Ronchi grating was obtained from the Qing Hua University and holographic plates of Triring (type GS-I) were used in the experiment. Table. (1) shows the conditions of development and fixing of the above films.

3.1.3 Encoding process of Method 3

The encoding procedure was the same as that of the Method 2 except that the film was bleached after developing and fixing. The bleaching agent was $K_3Fe(CN)_6$. After

Fresh film	Kodak TP 2415	Triring holographic plates (type GS-I)
Developer	HC-110 Dilution F	Kodak developer D 19 (various dilution)
Development Time	8 min	10-20 min, depending on dilution.
Development Temp.	20 °C	20 °C
Fixer	Ilford rapid fixer	Ilford rapid fixer
Fixing time	2 min	2 min
Fixing Temp.	20 °C	20 °C

Table(1) Development and fixing conditions of the films used in the Methods 2 and 3.

Fig. 3-1 The photographic enlarger.

bleaching, the wet encoded film was immersed in methanol and then ethanol and forced-dry under a hair drier, so that the formation of water marks was avoided. Similar to Method 2, the same Ronchi grating and holographic plates were used in this method.

3.2 Reconstruction Process

3.2.1 Reconstruction process of Method 1

A) Method 1A-Contrast reversal by Diffuse Transmission

The set-up is shown as in Fig. 3-2a. Two identical Philips bulbs 7748 (250W) supplied by variable power supplies were used as illuminating sources S1 and S2 with adjustable light intensities. The color filters employed which denoted as F_G and F_R, were Corning CS 4-55 (green, $x_A = 0.40$, $y_B = 0.55$) and CS 2-60 (red, $x_A = 0.72$, $y_B = 0.28$).

L1 and L2 are collimating lenses with focal lengths 250 mm and 160 mm; and diameters 9 mm and 4 mm respectively. The object film denoted as T was placed at plane-1 with emulsion side towards the lens L while the plane-2 is the image plane of the plane-1 with respect to lens L. The pseudocolored image was formed on the plane-2 by lens L. In fact, lens L and plane-2 form an ordinary camera system.

To obtain an adequate intensity balance at the output plane-2, the light intensities were adjusted to a suitable ratio. Furthermore, a ground glass diffuser G was placed in

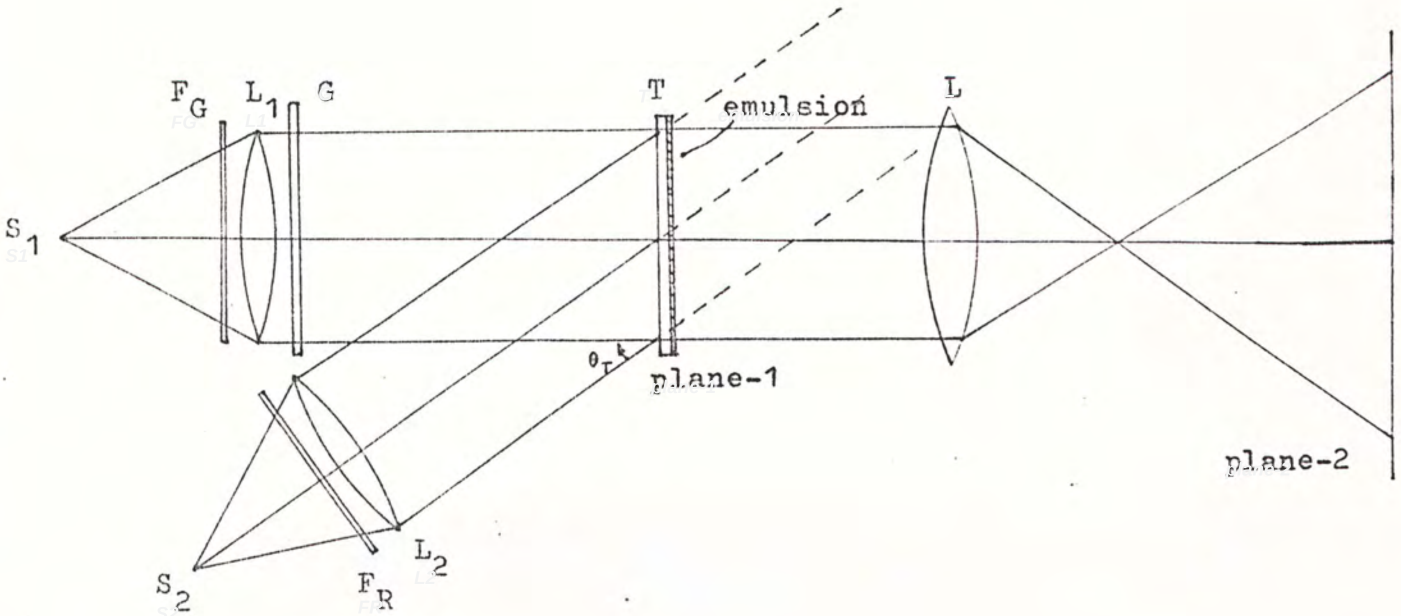

Fig. 3-2a Experimental set-up of Method 1A.

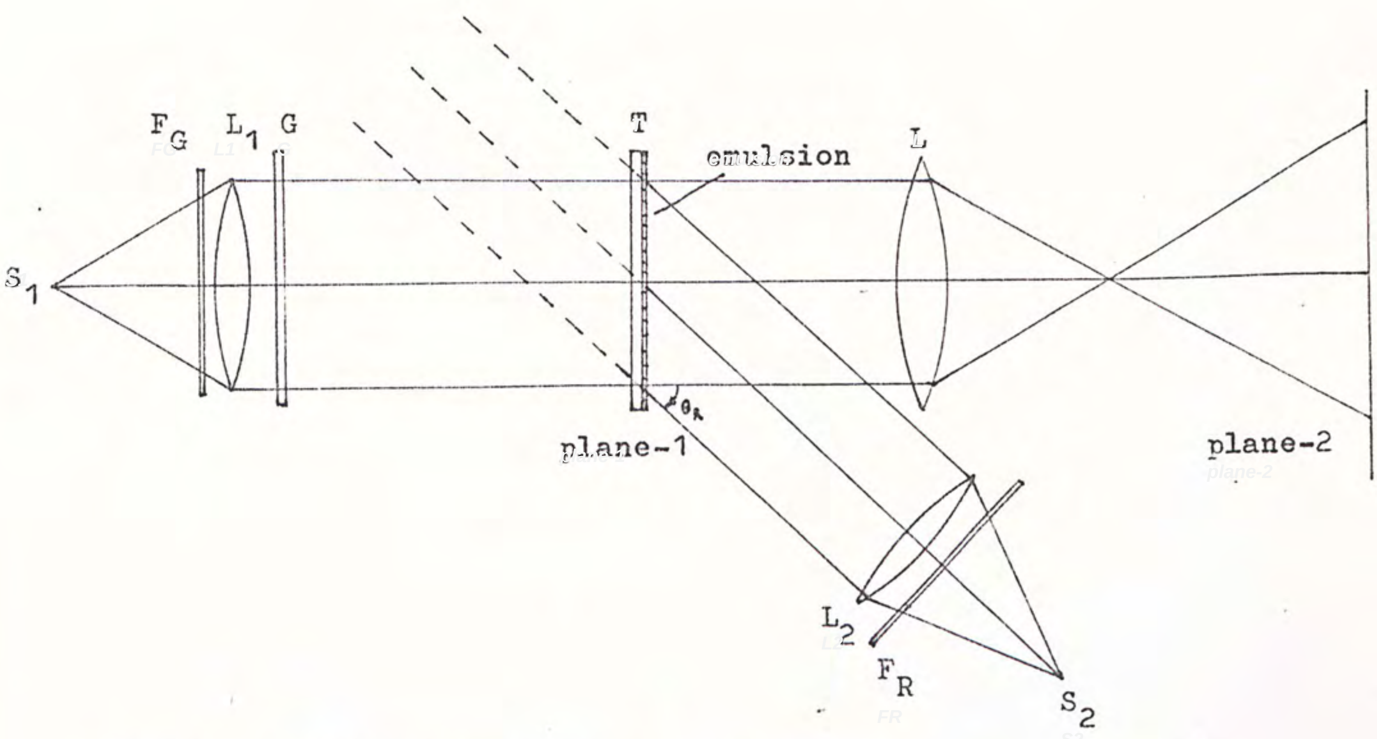

Fig. 3-2b Experimental set-up of Method 1B.

the direct beam from S1 to provide uniform illumination to the transmitted image. The angle between the two illumination beams is denoted as the scatter angle θ_T .

B) Method 1B-Contrast Reversal by Diffuse Reflection

The set-up is shown as in Fig. 3-2b. It is similar to part A except that the direction of the source S2 of the oblique illumination is on the side of the film plane-1. The angle between the two illumination beams is denoted as the scatter angle θ_R .

3.2.2 4 f Spatial Filtering System

Both Methods 2 and 3 involve spatial filtering. Nevertheless, the spatial spectra associated with the two methods are different, and the corresponding spatial filters are different.

The 4 f spatial filtering system is shown in Fig. 3-3. Two EL-NIKKOR (focal length 360 mm, f. 5.6) projector lenses were employed as the two fourier lenses. The point source was achieved by imaging the filament of a Philips bulb 7748 (250 w) on an adjustable diaphragm, and a collimating lens of focal length 310 mm was used to produce parallel beam of light. The diameter of the pinhole diaphragm was adjusted to about 1 mm in the experiment.

The two fourier lenses were postioned such that, the back focal plane of the first fourier lens coincided with the

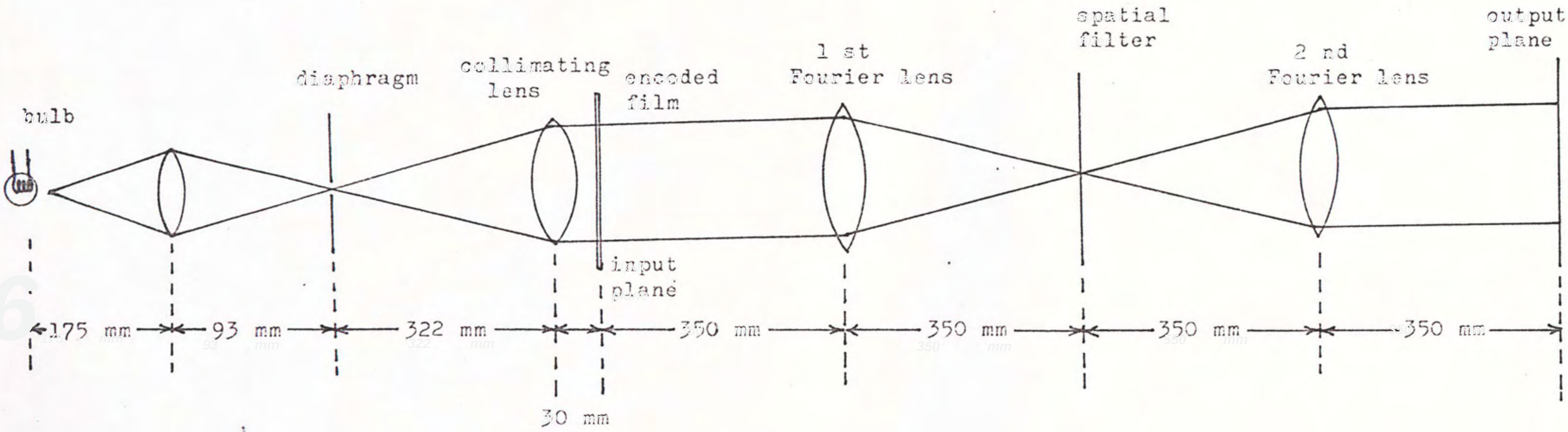

Fig. 3-3 The arrangement of the 4 f spatial filtering system.

front focal plane of the second one, and this plane is denoted as the spatial frequency plane. The front focal plane of the first fourier lens is denoted as the input plane, and the back focal plane of the second one is denoted as the output plane.

When the encoded film was placed at the input plane, its assciated spatial frequency spectrum would appear at the spatial frequency plane. After the spatial filter was put at this plane, the pseudocolored image would be formed at the output plane.

3.2.3 Reconstruction Process of Method 2

The encoded film was modulated in one direction by a Ronchi grating, so a row of colored diffraction spots would appear at the spatial frequency plane as in Fig. 3-4a. However, only the zero, 1 and -1 orders were used, all others were blocked up.

The spatial filter contains three holes for the above three orders to pass through with a green filter covering zero order hole and red filters covering the 1 and the -1 order holes as in Fig. 3-4b. Furthermore, a small piece of polarizer was placed over the zero order hole and a rotatable analyser was placed after the spatial filter. By rotating the analyser, the intensity of the zero order image could be varied.

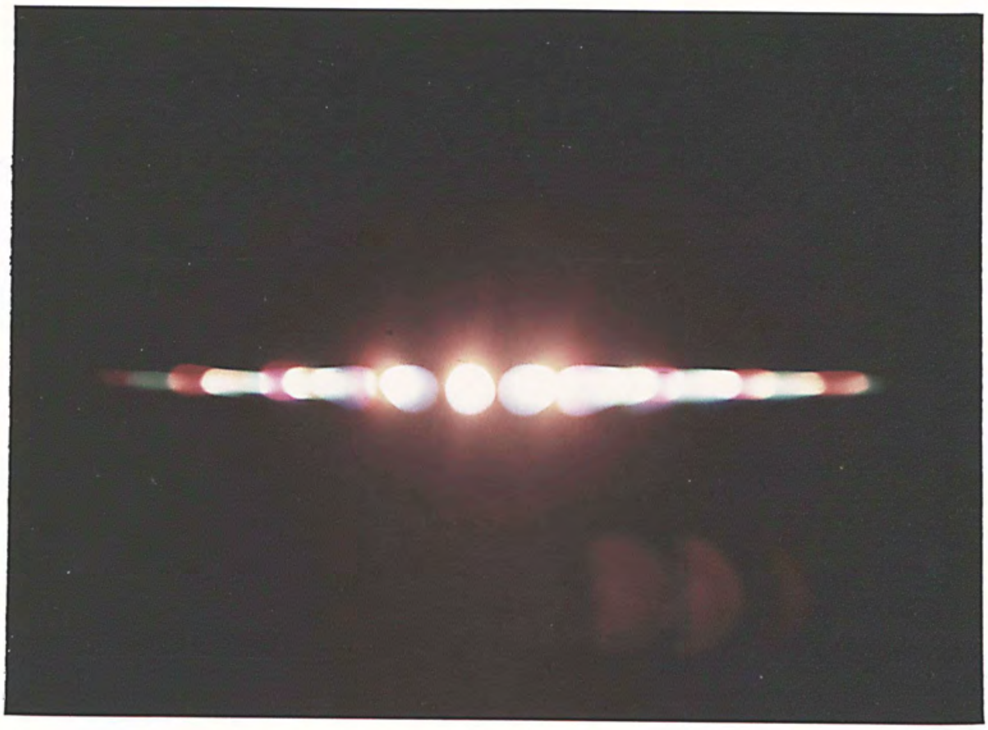

Fig. 3-4a Spatial frequency spectrum in Method 2.

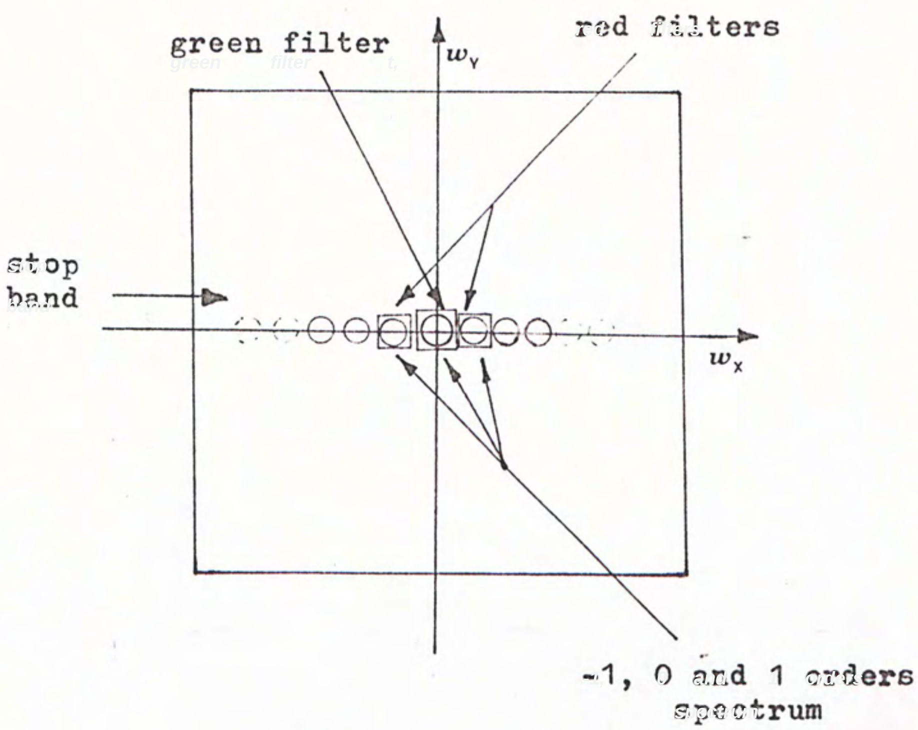

Fig. 3-4b Spatial filter of Method 2.

3.2.4 Reconstruction process of Method 3

Just as in Method 2, a row of colored diffraction spots appeared at the spatial frequency plane as shown in Fig. 3-5a.

A hole of suitable size was made on the spatial filter such that only the zero order or the first order could pass through as in Fig. 3-5b. As the zero order or the first order was allowed to pass through, different types of pseudocolored images were formed at the output plane respectively.

3.3 Recording of the pseudocolored image

The pseudocolored images of the above methods were recorded by a camera while both color films or slides can be used.

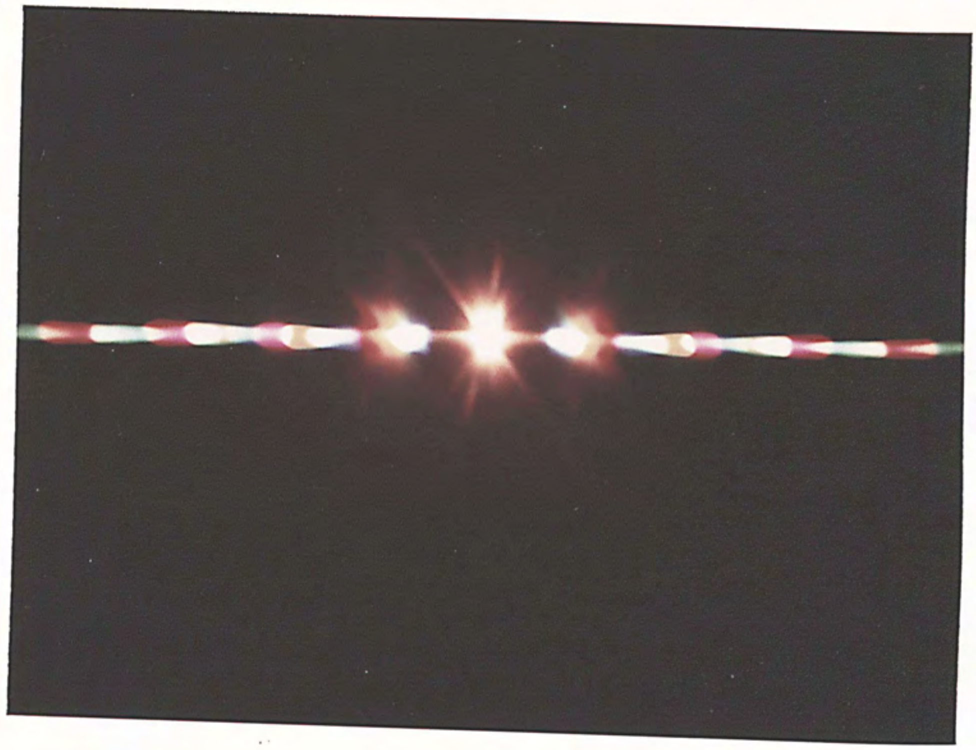

Fig. 3-5a Spatial frequency spectrum in Method 3.

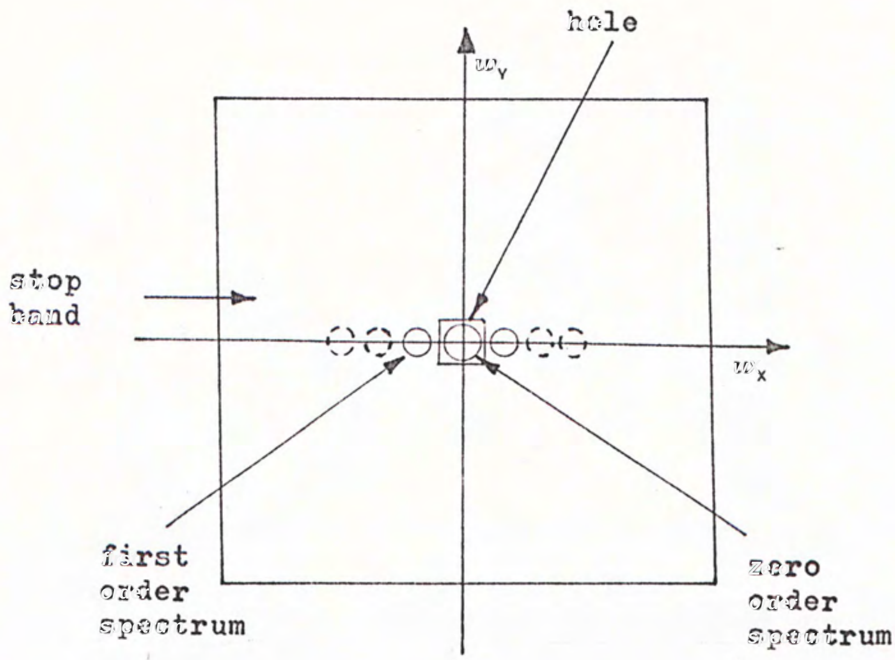

Fig. 3-5b Spatial filter of Method 3.

Chapter 4

Results and Discussion

Two object films as following were chosen for the study of the three pseudocolor encoding methods :

1. A Kodak photographic step (tablet no.2, CAT 152 3398) denoted as Film A is shown in Fig. 4-1 , it is a black and white gray scale and its intensity distribution is shown in Fig. 4-2 .
2. A dental X-ray picture of teeth denoted as Film B is shown in Fig. 4-3.

The pseudocolor encoding results of the above films by the three methods will be presented below; however, the color of the shown pictures is partly deviated from that of the original images, and the light green color appears to be yellow color.

4.1 Pseudocolor encoding results of Method 1A and 1B

As mentioned in Section 2.1, the pseudocolored image is formed by the simultaneous addition of a direct contrast image and a contrast reversed image, each one in different color. In Method 1, the direct contrast image is obtained by direct transmission, while the contrast reversed image can be

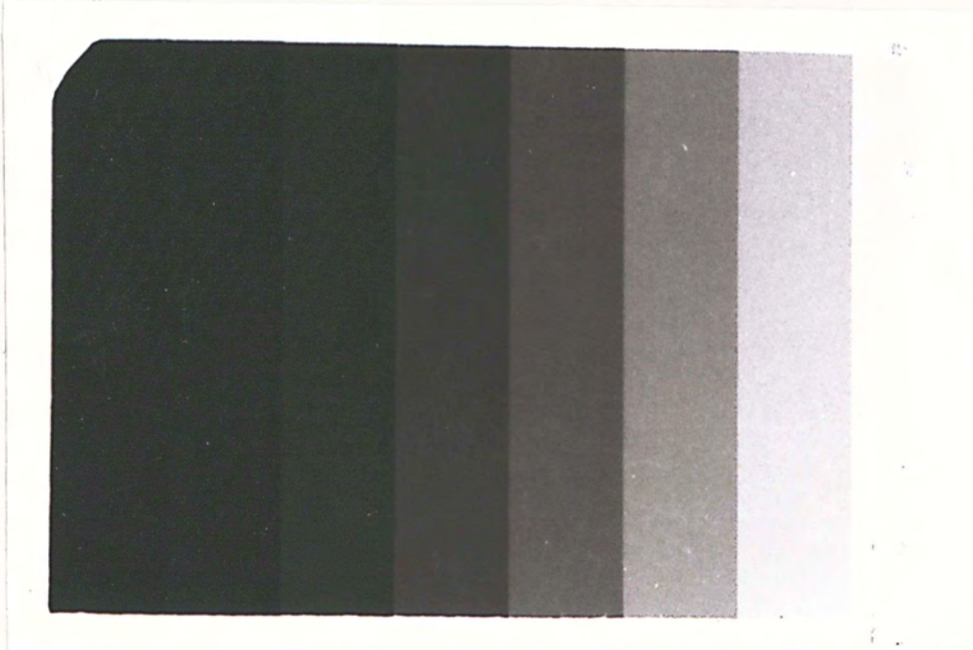

Fig. 4-1 Film A.

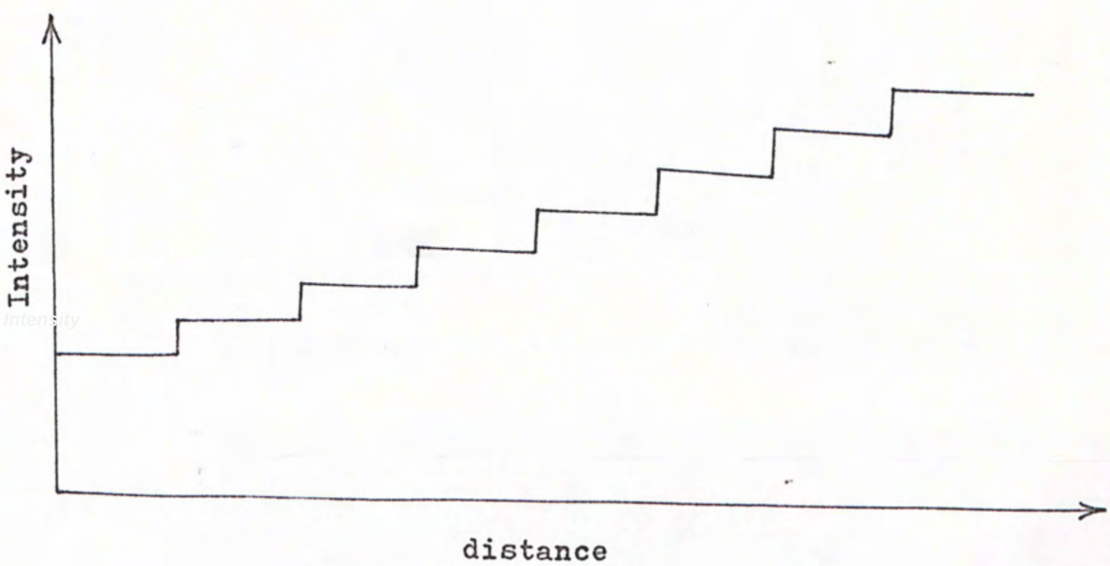

Fig. 4-2 Intensity distribution of Film A.

Fig. 4-3 Film B.

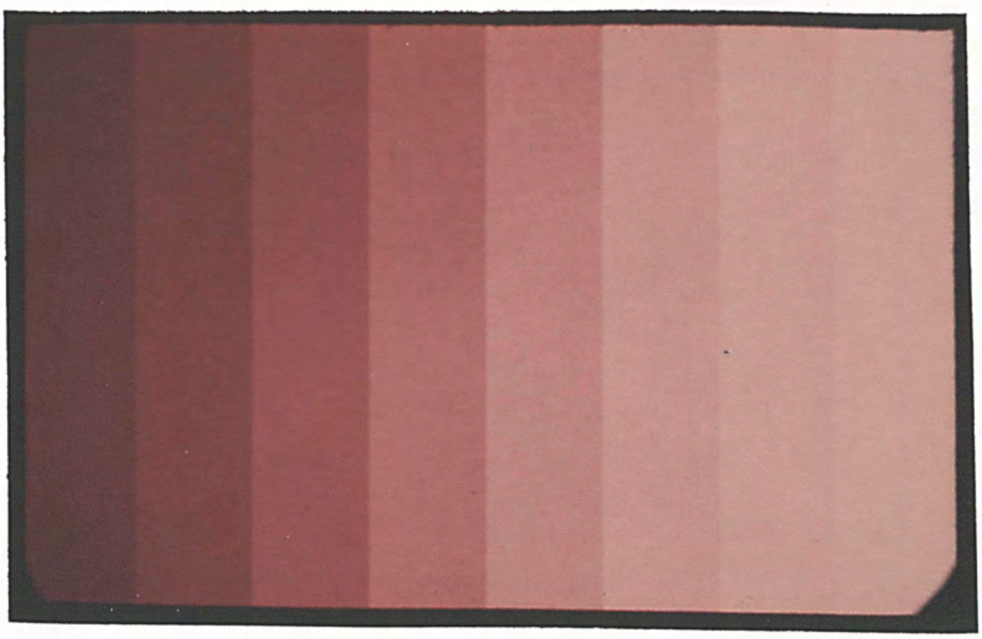

Fig. 4-4a Pseudocolor picture of Film A by Method 1A.

obtained either by diffuse transmission or by diffuse reflection, their results are slightly different.

Without loss of generality, the direct contrast image is encoded in green color, and the contrast reversed image is encoded in red color in both cases of Method 1. Thus, if the above two images are in ideal situation, we expected that the regions corresponding to high gray level would appear in a dominant red, and those parts of low gray level would be in a dominant green in the final pseudocolored image.

(A) Method 1A-contrast reversal by diffuse transmission

The pseudocolored images of Film A and Film B processed by Method 1A are shown in Fig. 4-4a and 4-4b . The scatter angle θ_T is 35° .

By looking at the above pictures, it was seen that the regions of low gray level are bright green, the regions of intermediate gray levels have bright red and orange colors, but the regions of high gray level appear to be dim red. This is different from the original expectation mentioned above. This phenomenon can be explained in the following paragraphs by the contrast reversal saturation effect.

From Section 2.2, we know that an approximate contrast reversed image will be obtained by diffuse transmission through the object film, because the scattered light intensity from any point on the film increases with the film density D at that point. However, when the density D of the

Fig. 4-4b Pseudocolor picture of Film B by Method 1A.

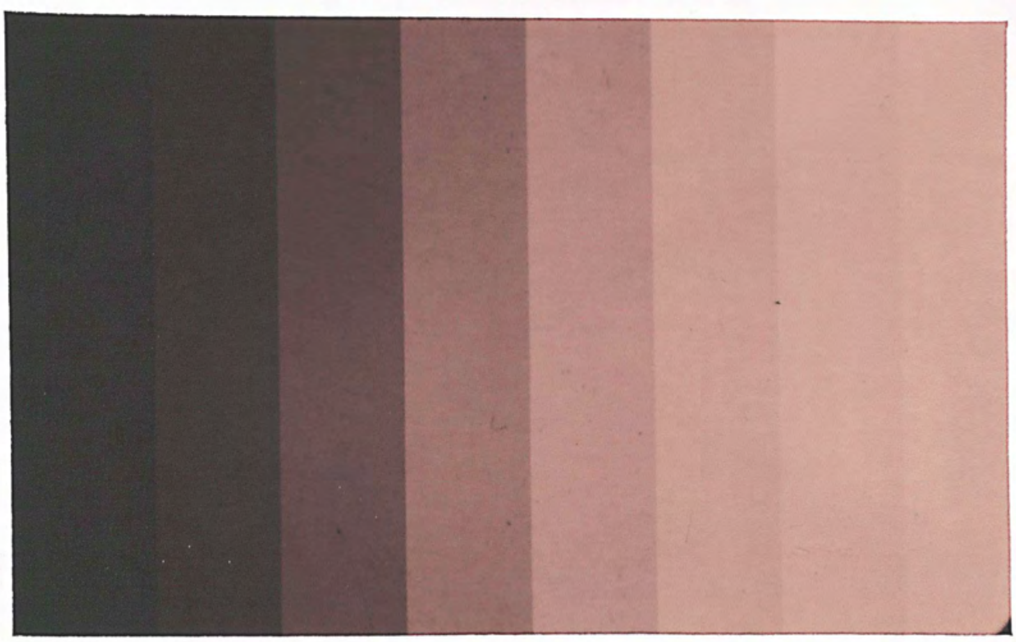

Fig. 4-5a The direct contrast image of Film A in green color.

of the film exceeds a certain value D_L, a saturation state reached, which can be attributed to multiple scattering, and then the scattered intensity begins to drop as the film density D increases further.

Fig. 4-5a shows the direct contrast image of Film A in green color by cutting off source S2 in Fig. 3-2a, and Fig. 4-5b shows the image of Film A by diffuse transmission in red color and Fig. 4-5c shows its intensity distribution. Obviously, Fig. 4-4a is simply the addition of Fig. 4-5a and 4-5b. We can see that the scattered light has its greatest contributions at certain intermediate gray levels instead of the highest one. It means that the contrast reversal holds for the range of film density D below the limit density D_L; beyond this limit, the contrast reversal can not be achieved. The regions of high gray level have little contribution from both images, that is the reason why the high gray level regions appear to be dim red.

The limit density D_L varies with the scatter angle θ_T. However, a maximum value is reached when the angle is about 30°.

(B) Method 1B-contrast reversal by diffuse reflection

The pseudocolored images of Film A and Film B processed by Method 1B are shown in Fig. 4-6a and 4-6b. The scatter angle θ_R is 45°.

By observation, we find that the above pictures have

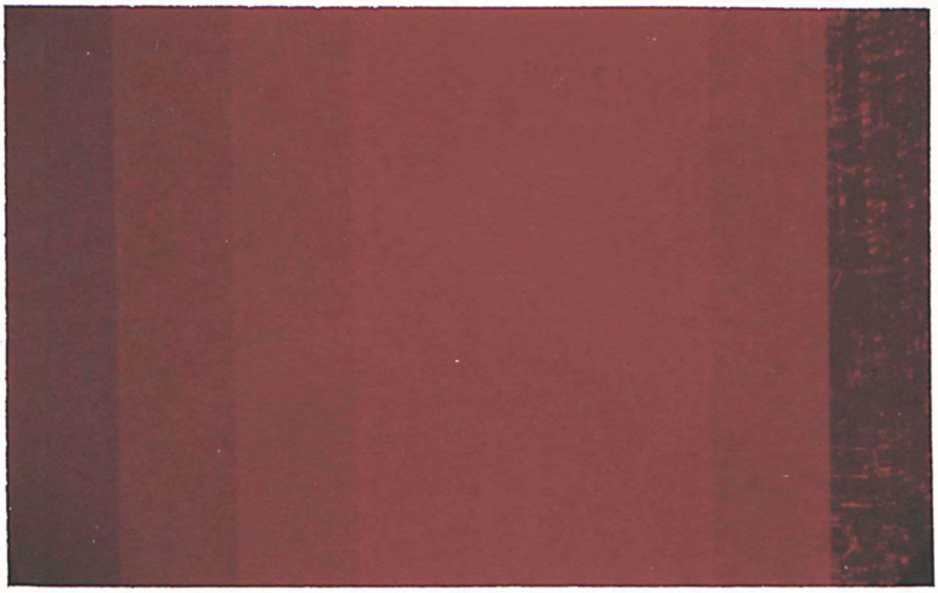

Fig. 4-5b The image of Film A by diffuse transmission in red color.

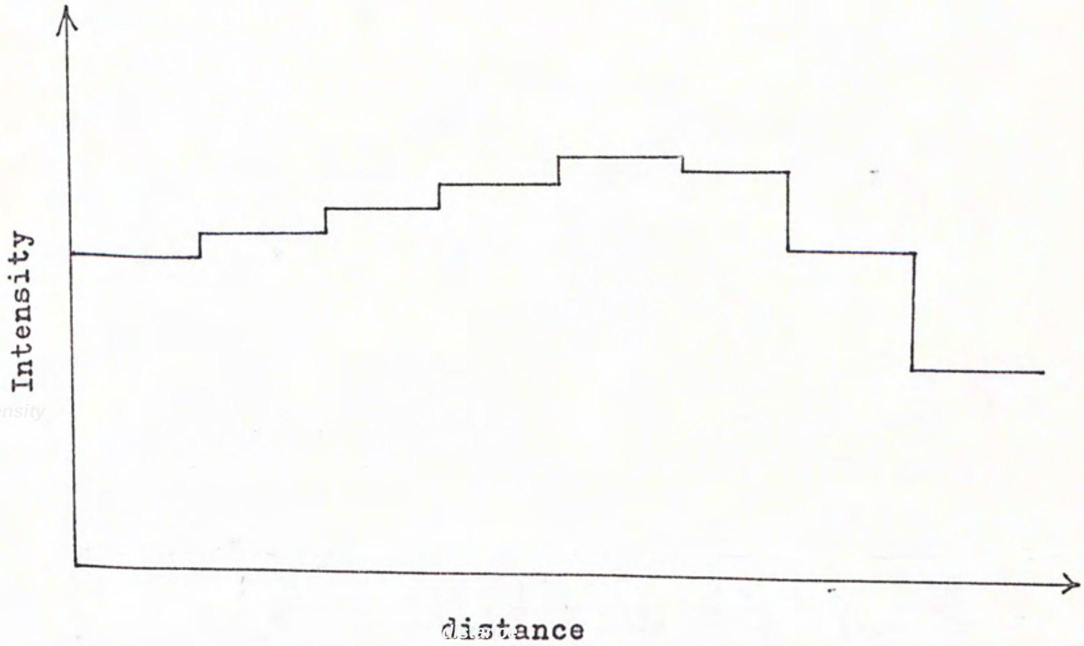

Fig. 4-5c The intensity distribution of the image of Film A by diffuse transmission.

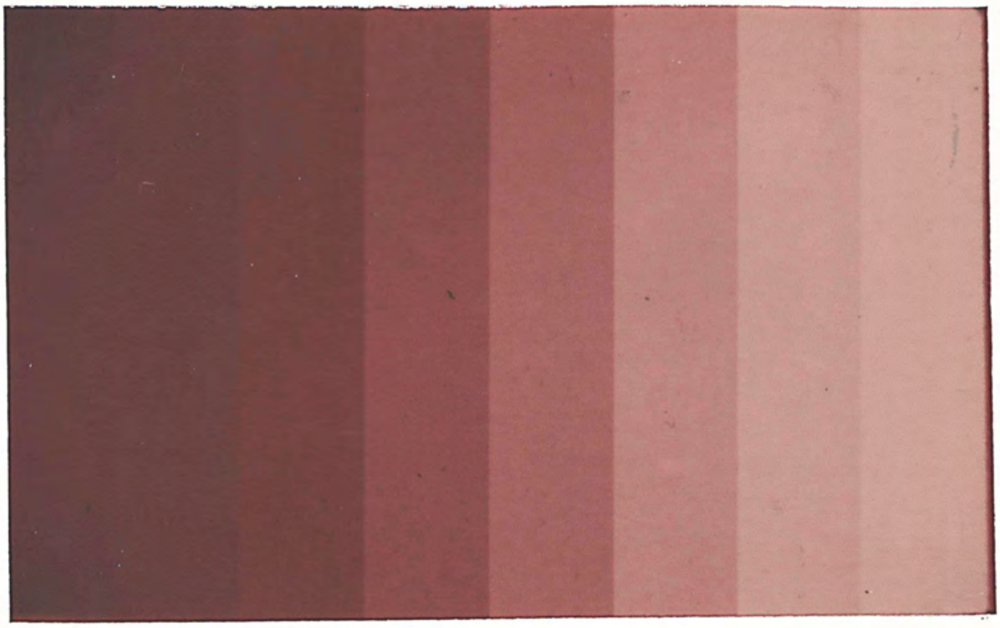

Fig. 4-6a Pseudocolor picture of Film A by Method 1B.

Fig. 4-6b Pseudocolor picture of Film B by Method 1B.

the following appearence in color. Most regions appear to be either bright red or bright green; dim red color does not appear. Likewise, the above appearence can be explained by a different type of contrast reversal saturation effect.

The image of Film A by diffuse reflection in red color is shown in Fig. 4-7a and its intensity distribution is shown in Fig. 4-7b . Fig. 4-6a is simply the addition of Fig. 4-5a and 4-7a.

From Fig. 4-7b, we note that the scattered light intensity quickly rises to a certain value and then keeps constant instead of dropping as the density D increases gradually. That results in the high contributions of scattered light in both intermediate and high gray levels. On the other hand, the direct transmitted light gradually decreases as the density D increases. Eventually, the range of density that obtained equal contributions from both the direct transmitted light and the diffuse transmitted light is very narrow. As mediate color will come out when the two contributions are nearly the same, there is seldom mediate color in the results of Method 1B.

Comparing the results of Method 1A and 1B, we can say that both processes have similar color qualities. However, the colors in the high gray level regions are slightly different for the two methods as mentioned above. The colors found on those pictures are mainly green, red and orange, other colors seldom appear; in fact, the colors obtained by both methods are not rich.

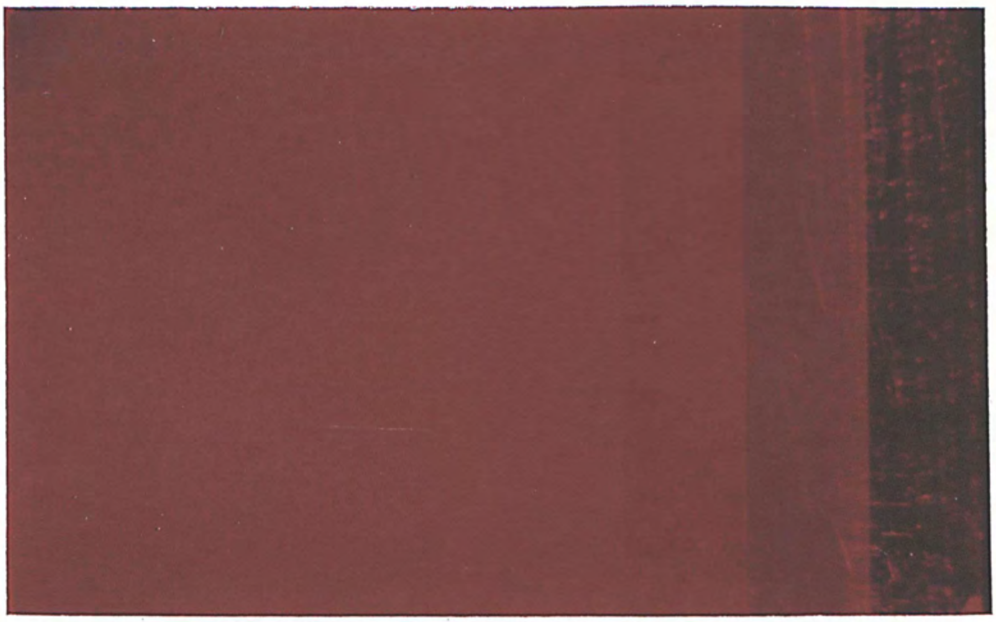

Fig. 4-7a The image of Film A by diffuse reflection in red color.

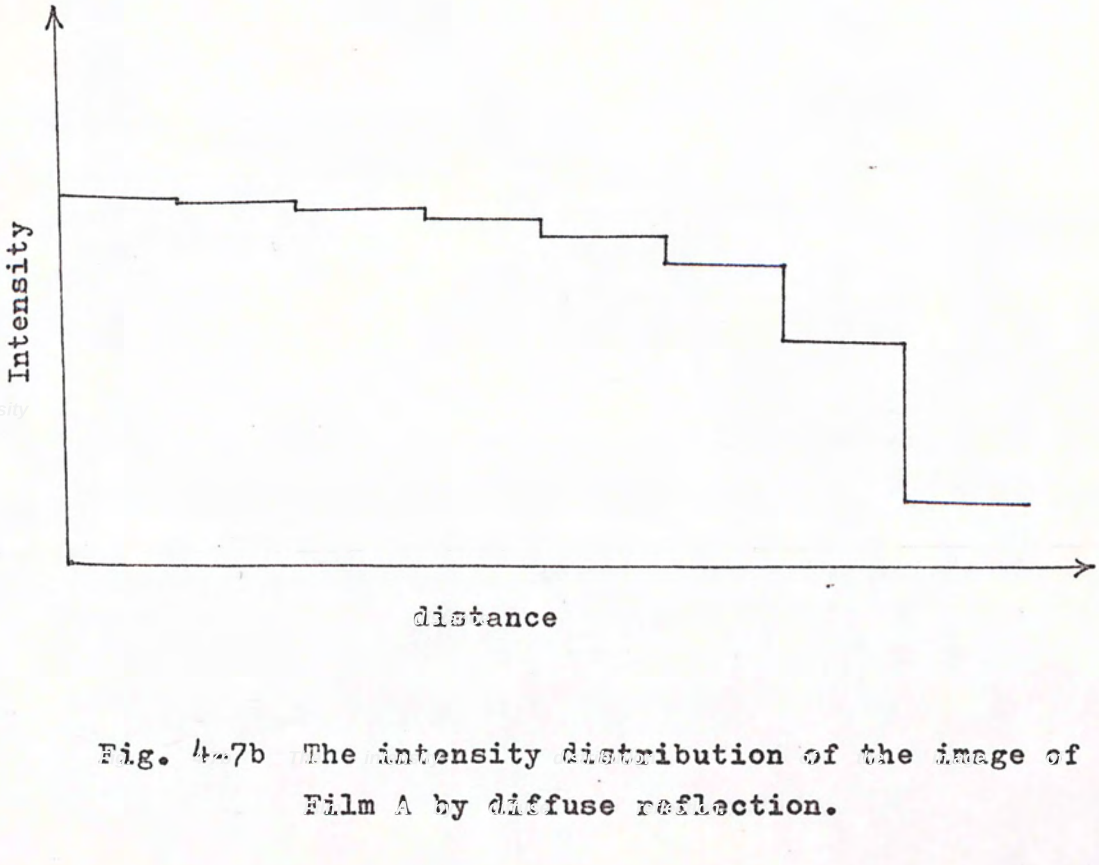

Fig. 4-7b The intensity distribution of the image of Film A by diffuse reflection.

It should be pointed out that, pseudocolor pictures of both Methods 1A and 1B have high resolution. Because of no need of modulation and spatial filtering, information loss is minimum.

The simplicity of procedures and the high resolution and strong output intensity of the final image greatly facilitate the utilization of Method 1, nevertheless, the color quality seems unsatisfactory.

As the variation of color in the final image is small, the range of color which different gray levels correspond to is small too. That implies the low sensitivity of Method 1.

It was mentioned in Section 3.1.1 that, the contrast reversal effect depends on the scattering properties of the emulsion type. In other words, different types of film will have a slightly different result.

4.2 Pseudocolor encoding results of Method 2

Similar to Method 1, a direct contrast image encoded in green color and a contrast reversed image encoded in red color are added together to obtain the pseudocolored image. The direct contrast image is obtained from the zero diffraction order of the spatial spectrum, and the contrast reversed image is obtained from the first order.

The pseudocolor pictures of Film A and Film B by Method 2 are shown in Fig. 4-8a and 4-8b . By observation of the

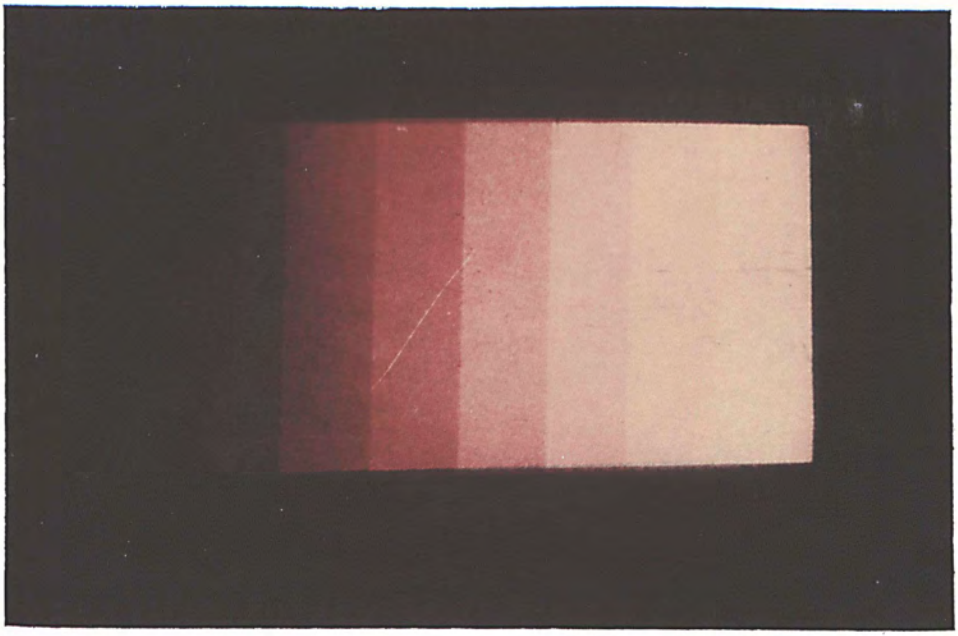

Fig. 4-8a The pseudocolor picture of Film A by Method 2.

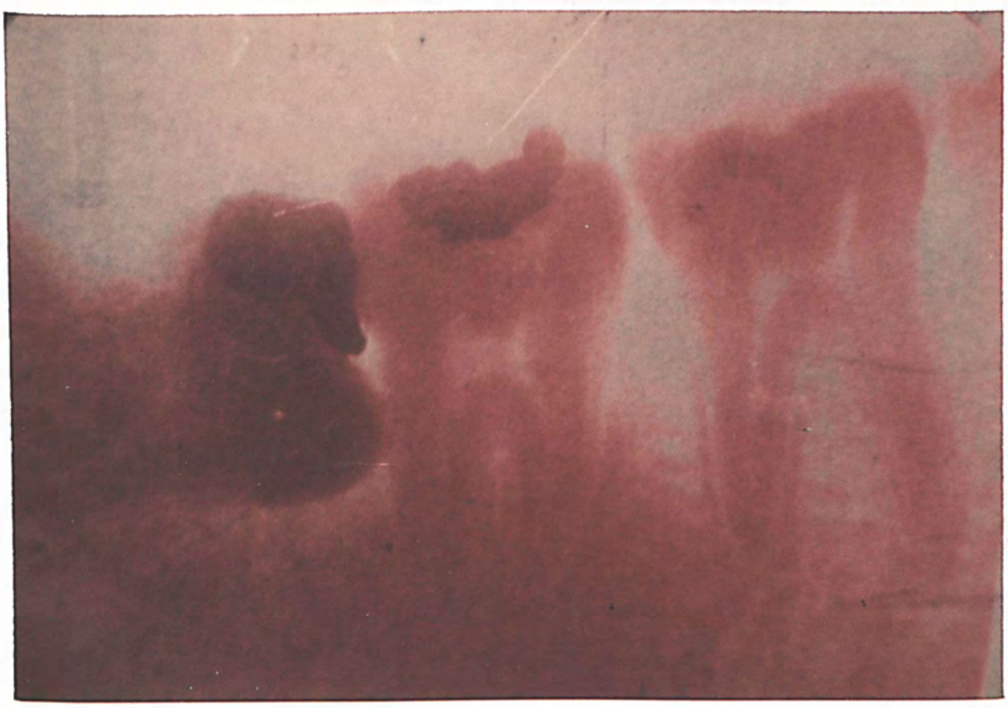

Fig. 4-8b The pseudocolor picture of Film B by Method 2.

above pictures, we find yellow color besides green, red and orange, and that does not appear in the pseudocolor pictures of Method 1. Therefore, we can say that the color in the results of Method 2 is richer than that of Method 1.

Furthermore, there is a phenomenon similar to Method 1A; the high gray level regions appear to be dim red. This is in part due to the halation problem associated with the modulation of the encoded film, but also to a large extent to the saturation problem in the exposure of the encoded film.

Light that penetrates the film emulsion may be reflected from the back of the base and so strike the emulsion once again, this will cause exposure beyond the exposed regions, and this effect is called halation. Through the modulation with Ronchi grating in the encoding process, the object image is sampled by equal width and spacing clear lines as shown in Fig. 4-9a, where clear line means transparent line. However, by means of halation, the width of the clear lines at the high exposure regions will become smaller than the original one as shown in Fig. 4-9b. Finally, the contribution of the high gray level regions of the encoded film to the first order spatial spectrum will be reduced. This effect is opposite to the contrast reversal effect, and leads to the saturation of contrast reversal at the high density regions.

On the other hand, if the contrast of the encoded film is too large, such that the exposure of some regions is saturated and above the linear range of the characteristic

Fig. 4-9a Enlarged picture of the clear lines at normal exposure.

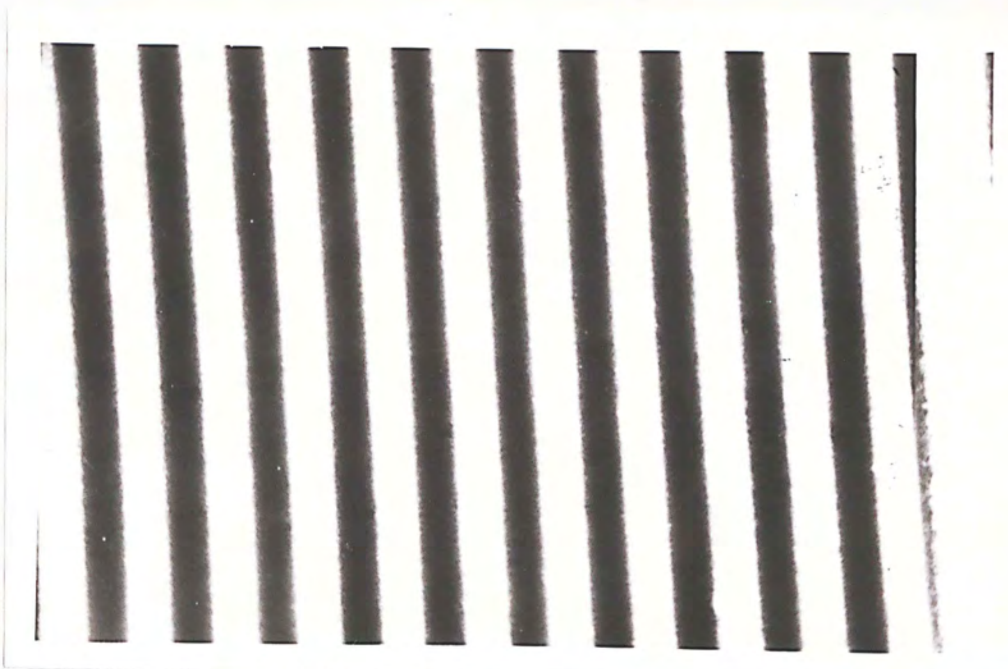

Fig. 4-9b Enlarged picture of the clear lines at high exposure.

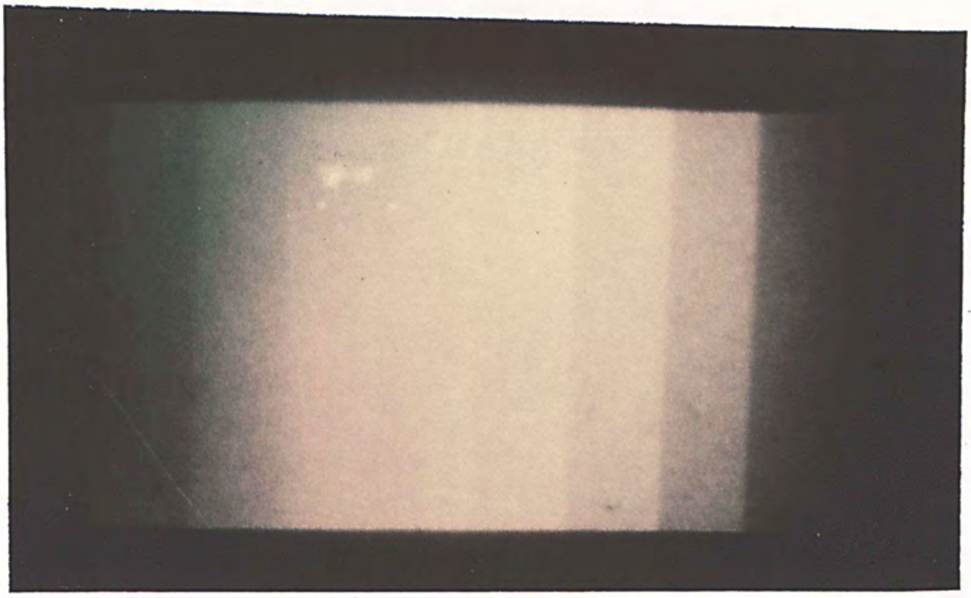

Fig. 4-10a The contrast reversed image of Film A from the first order with the exposure time of the encoding process of 30 sec.

Fig. 4-10b The contrast reversed image of Film A from the first order with the exposure time of the encoding process of 1 min.

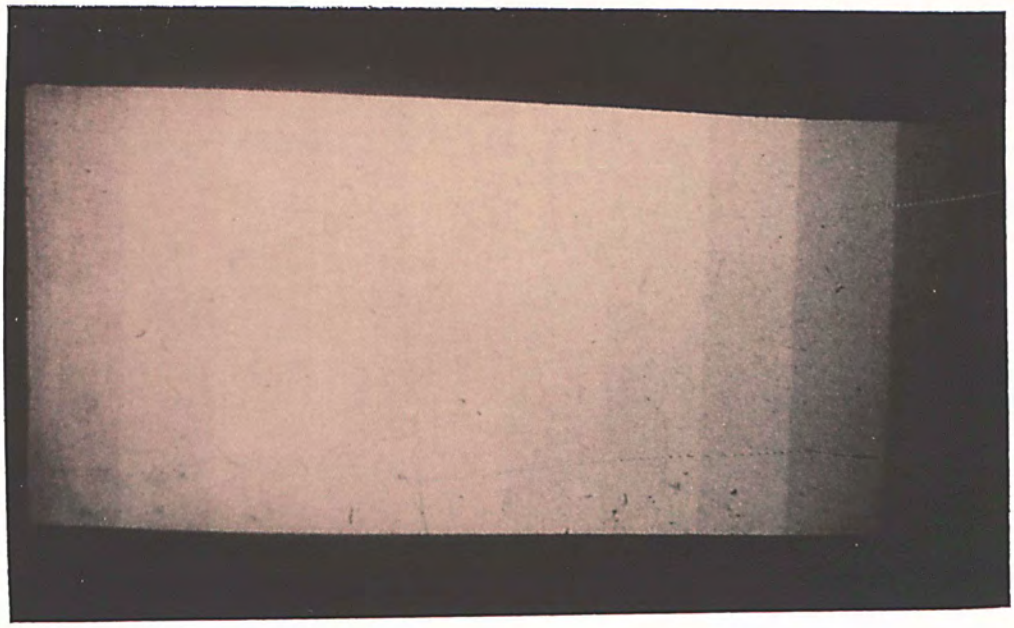

Fig. 4-10c The contrast reversed image of Film A from the first order with the exposure time of the encoding process of 2 min.

Fig. 4-10d The contrast reversed image of Film A from the first order with the exposure time of the encoding process of 3 min.

curve of the film, then the contrast reversal effect can not be achieved in that regions.

Fig. 4-10a, 4-10b, 4-10c and 4-10d show the contrast reversed images of Film A from the first order with different exposures of encoding process. Their exposure values are 30 sec, 1 min, 2 min and 3 min respectively. We can see that the brightest part of each picture appears at certain intermediate gray levels instead of the highest level, and has its position slowly shifted towards the lower gray level as exposure increases gradually. In fact, this is in agreement with our reasoning. As the exposure increased, more regions are saturated in exposure, and this leads to the shift of the brightest part to the lower gray levels.

The resolutions of the pseudocolor pictures are much lower than that of Method 1, the images are slightly blurred. Since modulation and spatial filtering are required in the processing, parts of the information must be blocked by the black lines of the Ronchi grating and the spatial filter, then it leads to a loss of spatial resolution in the final image.

The output intensity of the pseudocolor image is weaker than that of Method 1, so the intensity efficiency is lower.

4.3 Pseudocolor encoding results of Method 3

Unlike that of Method 1 and 2, the pseudocolored image is obtained by establishing a relation between the output intensity and the film density D, instead of the addition of a direct contrast image and a contrast reversed image. Therefore, a quite different result in the pseudocolored image is expected.

The pseudocolored image of Method 3 can be obtained by either the contribution of the zero order of the spatial spectrum or that of the first order independently. The zero order output pseudocolored images of Film A and Film B of Method 3 are shown in Fig. 4-11a and 4-11b, and that of the first order output are shown in Fig. 4-12a and 4-12b .

By looking at the above pictures, we find that the bright white regions in the zero order output pseudocolored image will appear to be dark in the corresponding first order output pseudocolored image. Furthermore, a color appear in the zero order output picture will appear to be its complementary color in the first order one. However, by means of the conservation of energy, there is no difficulties to explain the above complementary effect of the two color images.

Since the zero and the first orders of the spatial spectrum are the dominant part of the whole spatial spectrum, other orders are negligible comparing to them. If the energy from a point of the input plane within a certain range of wavelength go to the zero order of the spatial spectrum, then the rest of the energy in the remaining range of the wavelengths must go to the first order. Finally, regions of a

Fig. 4-11a The zero order pseudocolor picture of Film A by Method 3.

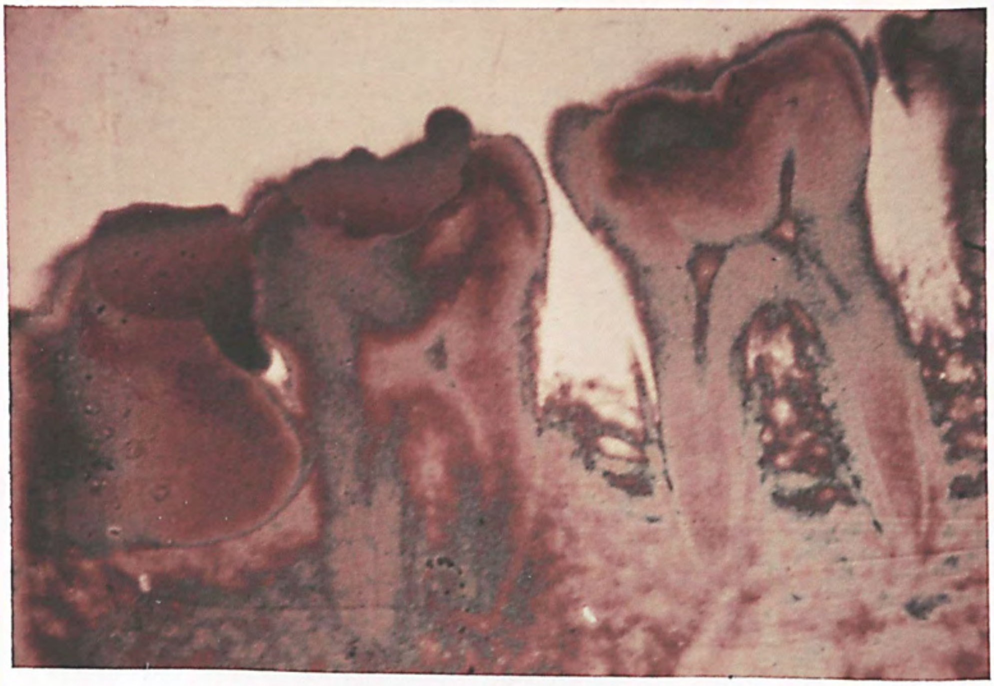

Fig. 4-11b The zero order pseudocolor picture of Film B by Method 3.

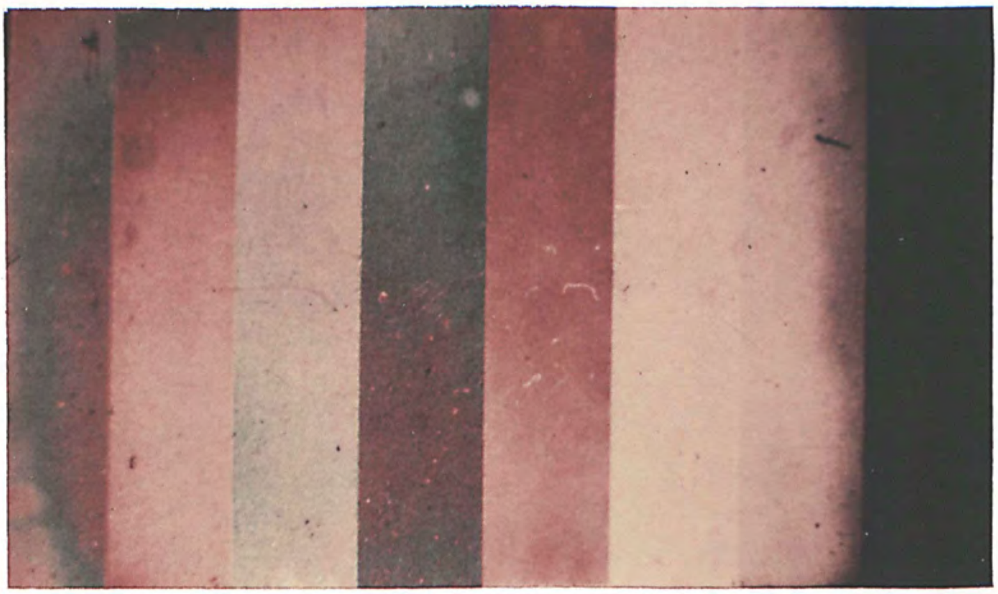

Fig. 4-12a The first order pseudocolor picture of Film A by Method 3.

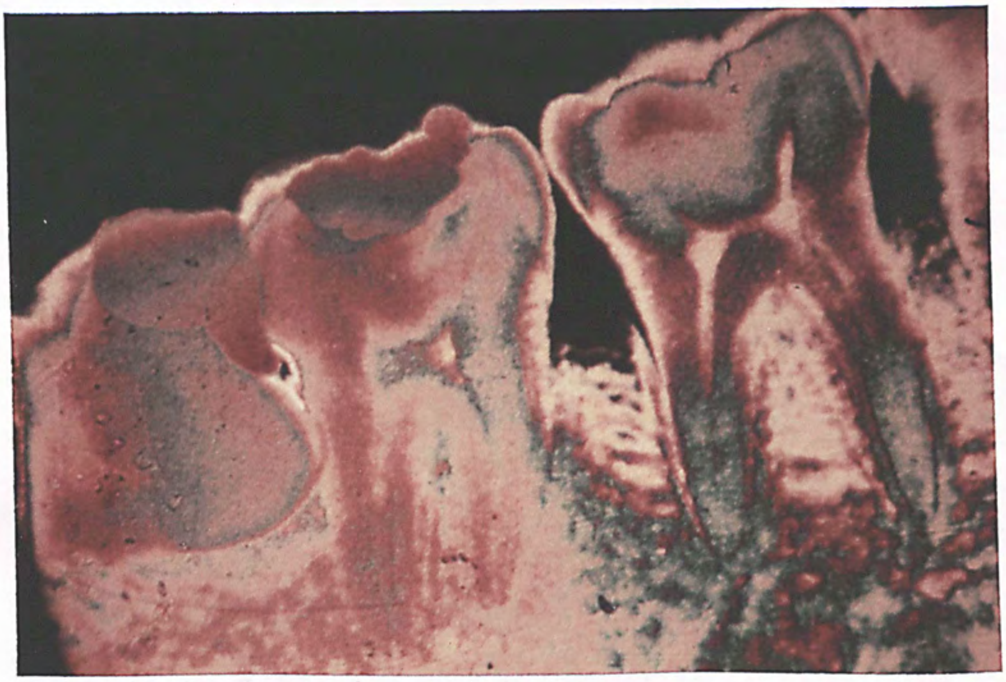

Fig. 4-12b The first order pseudocolor picture of Film B by Method 3.

color in the output image of one order will be in conjugate with regions of its complementary color in the output image of another order.

The color varieties of the pictures are much richer than that of either Method 1 or Method 2. Many colors appear besides red, green and yellow. However, by observations of Fig. 4-11a and 4-12a, we note that certain colors have tendency to reappear even the corresponding gray levels of the object film are different, so there exists a risk of confusing different gray levels.

Refering to section 2.3, we know that the output intensity for a given wavelength has a periodic relation with the object film density D, so there are probabilities of the reappearence of a color corresponding to different gray levels. Actually, the period of color reappearence can be affected by the bleaching agent and the contrast of the encoded film.

The kind of silver salt formed on the encoded film is determined by the bleaching agent, and so is the refractive index of the salt. Silver salt of greater refractive index will result in shorter period of reappearence.

On the other hand, the concentration of the developer used during encoding will affect the contrast of the encoded film and then the reappearence period. Fig. 4-13a, 4-13b and 4-13c show different zero order pseudocolored images of Film A made in different concentrations of the developer, where the developer is diluted with water in ratios of 1/10, 1/15

Fig. 4-13a The zero order pseudocolor picture of Film A.
Developer dilution 1:10 .

Fig. 4-13b The zero order pseudocolor picture of Film A.
Developer dilution 1:15 .

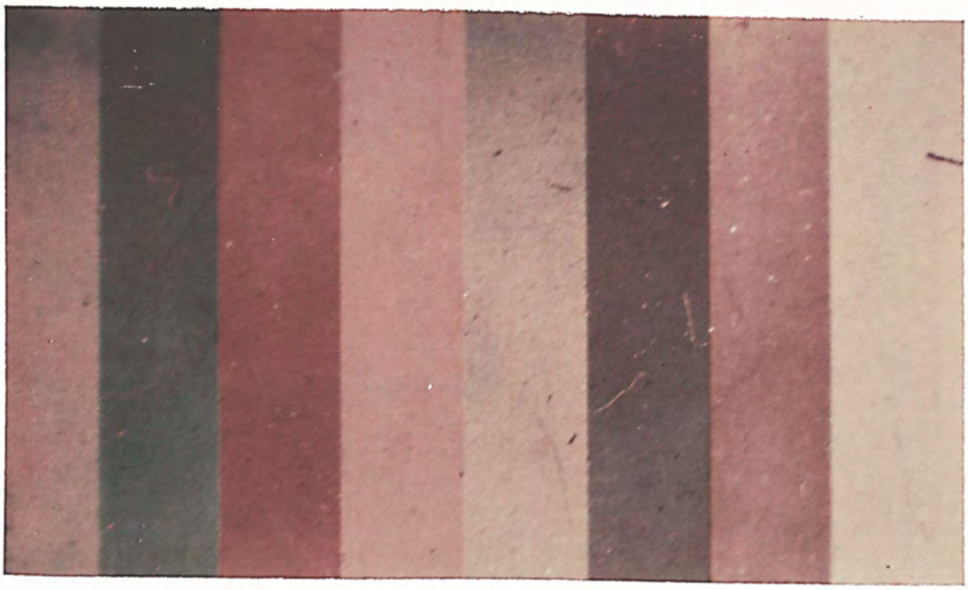

Fig. 4-13c The zero order pseudocolor picture of Film A.
Developer dilution 1:20 .

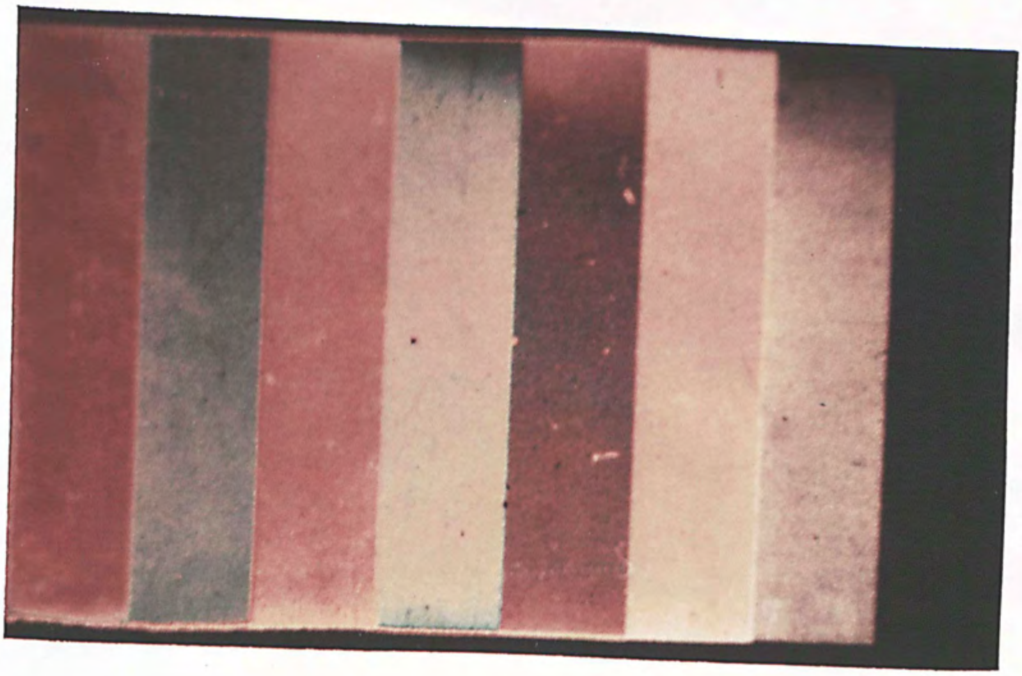

Fig. 4-14a The first order pseudocolor picture of Film A.
Developer dilution 1:10 .

and 1/20. The corresponding first order pseudocolored images are shown in Fig. 4-14a, 4-14b and 4-14c.

Obviously, we note the tendency of the reappearence period to become longer as the concentration of the developer decreases, that is in agreement with the theory.

Furthermore, the pseudocolor effect of this method can be achieved when the exposure of the encoding process is over a minimum value; otherwise, a black and white image will be obtained. Pseudocolor pictures of Film B with ascending exposure values of 15 sec, 30 sec and 45 sec are shown in Fig. 4-15a, 4-15b and 4-15c. We can see that there is no color in Fig. 4-15a, but some appear in Fig. 4-15b and Fig. 4-15c is the most colorful one. Fig. 4-16a, 4-16b and 4-16c show the corresponding first order pseudocolor pictures.

From Fig. 4-11a and 4-12a, it is also observed that the color of successive gray levels seem to be very different, this effect emphasizes the high sensitivity of this encoding method. A small change in gray density will result in great change in color, so that any small density variation can be easily observed by naked eye. However, the high sensitivity of Method 3 leads to the following difficulties of the experiment.

At first, the projecting light for the encoding process should be highly uniform, otherwise defects will be introduced. Actually, the non-uniformity of the colors in the pseudocolor pictures of Film A processed by Method 3 is raised by this effect.

Fig. 4-14b The first order pseudocolor picture of Film A. Developer dilution 1:15 .

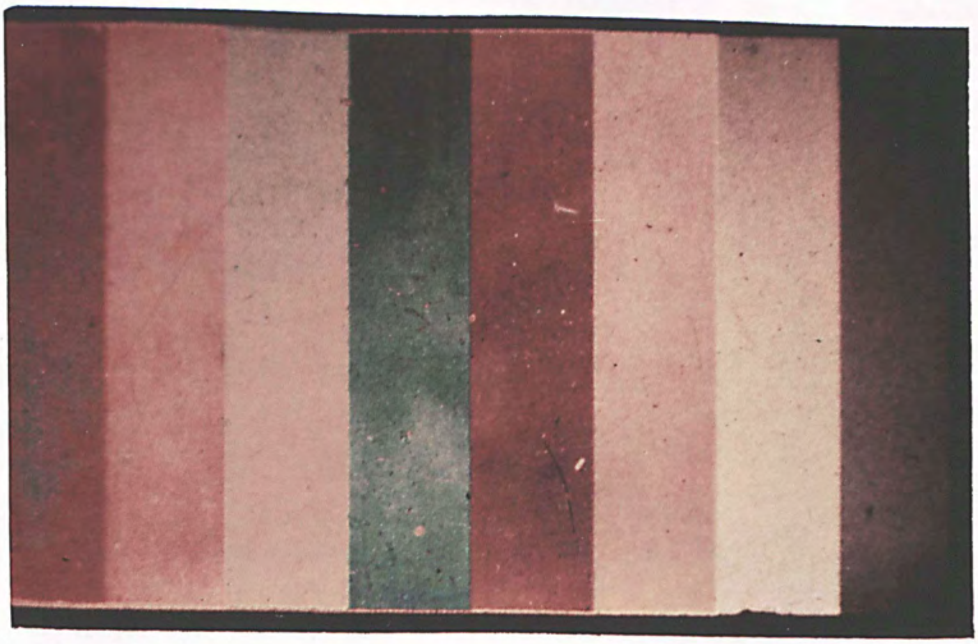

Fig. 4-14c The first order pseudocolor picture of Film A. Developer dilution 1:20 .

Fig. 4-15a The zero order pseudocolor picture of Film B with exposure time of the encoding process of 15 sec.

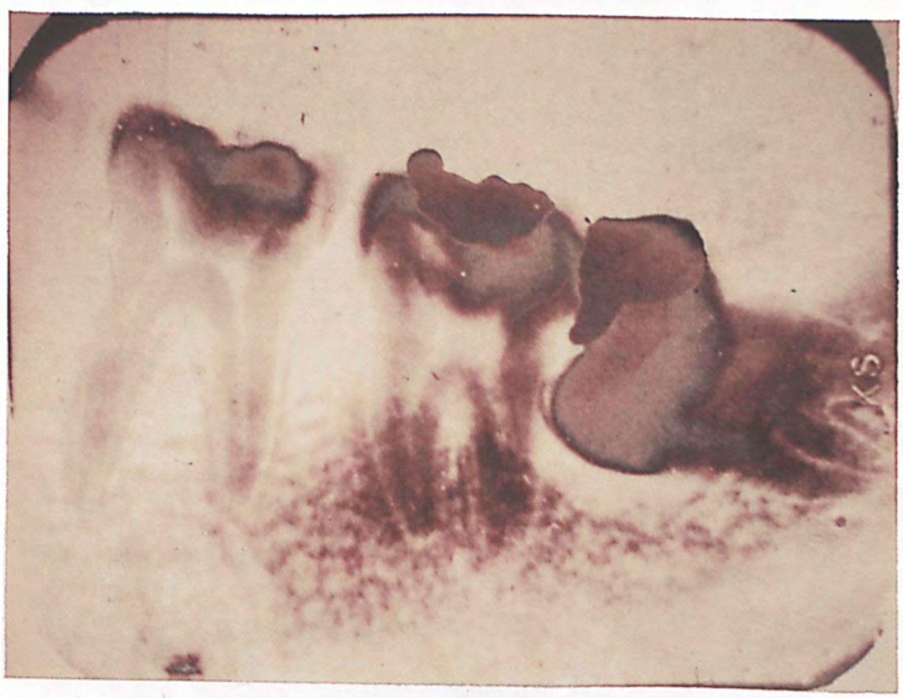

Fig. 4-15b The zero order pseudocolor picture of Film B with exposure time of the encoding process of 30 sec.

Fig. 4-15c The zero order pseudocolor picture of Film B with exposure time of the encoding process of 45 sec.

Fig. 4-16a The first order pseudocolor picture of Film B with exposure time of the encoding process of 15 sec.

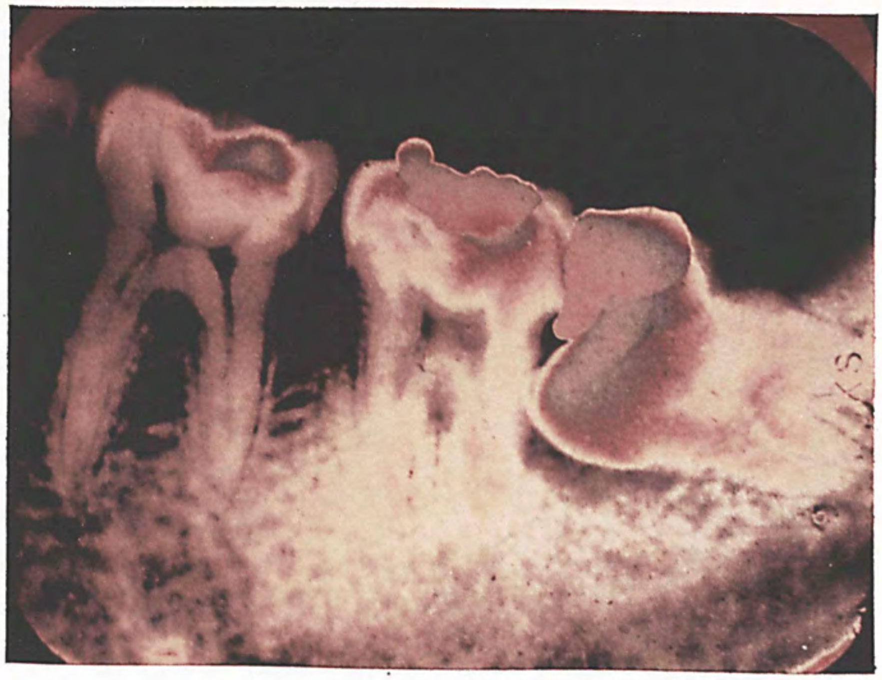

Fig. 4-16b The first order pseudocolor picture of Film B with exposure time of the encoding process of 30 sec.

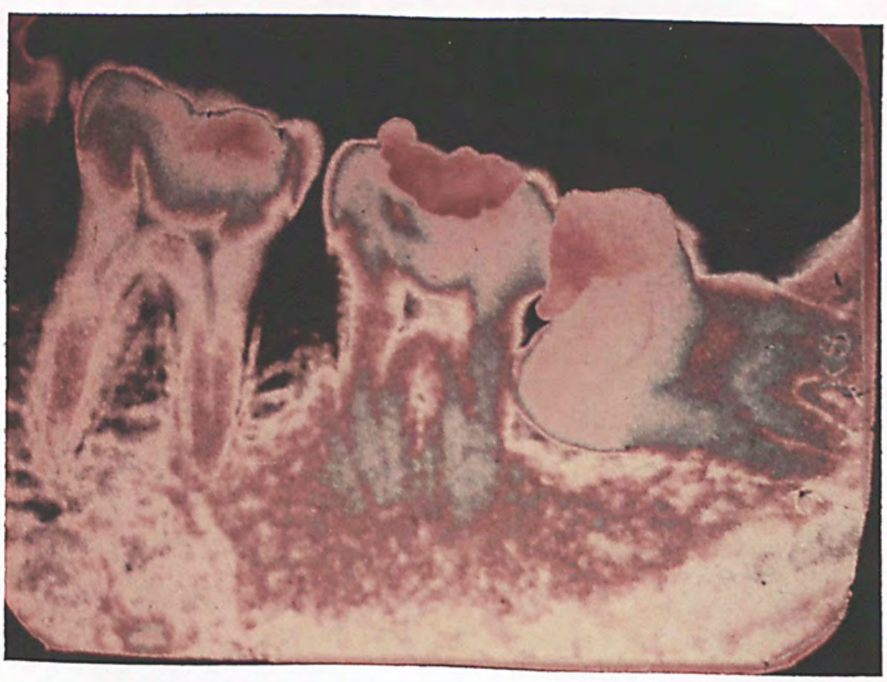

Fig. 4-16c The first order pseudocolor picture of Film B with exposure time of the encoding process of 45 sec.

Secondly, after encoding process, the wet film should be dried with great caution to prevent the formation of water marks. Water marks formed on the film will vary the thickness of the silver salt and so is the optical path length of that region, then the color information will be partly deviated. In our experiment, the wet film was immersed in methanol and ethanol successively; in this way, the film can be dried quickly without formation of water marks.

The output intensity of Method 3 is much higher than that of Method 2. As the encoded film was bleached, more light can pass through the film and results in stronger output image.

Chapter 5

Conclusion

Three methods of optical density pseudocolor encoding were studied and their results were presented with discussions. The characteristics of each method were investigated and comparison were made among them.

Method 1 was found to have the advantages of simplicity, high resolution in output image and strong output intensity; however, the color quality is unsatisfactory. The results of Method 2 have very low resolution and output intensity, but the color is a bit richer than that of Method 1. Since both methods are not very sensitive to small changes in gray levels, they seem to need further improvement.

With regard to Method 3, it has very colorful results and strong output intensity, and it is so sensitive to the gray level that even a very small change in gray level leads to great difference in color. However, this method suffers one major drawback that one color of the output image may correspond to two gray levels, so there exists a risk of confusing different gray levels.

Finally, we can say that Method 3 is the most potential one of the three methods, particularly in the encoding of high contrast pictures. The high sensitivity of the method facilitate the differentiation of small variation in density which is difficult to discriminate by eye.

REFERENCES

1. J. Rheinberg, J.R.Microsc. Soc. 373(August 1896).

2. H.K. Liu and J.W. Goodman, Nouv. Rev. Opt. 7(1976)285.

3. G. Indebetouw, Appl. Opt. 7(1977)1951.

4. J. Santamaria, M.Gea and J. Bescos, J. Optics 4(1979)151.

5. T.H. Chao, S.L.Zhuang and F.T.S.Yu, Opt. Lett. 5(1980)230.

6. S. Guel, J. Santamaria and J. Altamirano, Proceed. AIP 65(1981)425.

7. G. Rodriguez, L. Ortiz and M. Moreno, Optics Comm. 38(1981)10.

8. R. Arizaga and N. Bolognini, Optics Comm. 43(1982)12.

9. R. Grousson, M. Henry and S. Mallick, J. Optics 13(1982)138.

10. F.T.S.Yu, X.X.Chen and T.H. Chao, J. Optics 15(1984)55.

11. J.A. Mendez and M.Nieto-Vesperinas, Appl. Opt. 22(1983)2068.

12. L.R. Berriel-Valdos, E. Jara, S. Guel and J. Ibarra, Optics Lett. 9(1984)196.

13. K. Hui and Z.M. Li, Acta Optica Sinica 3(1983)298.

14. 郭履容等,《光學學報》, 4(1984)145.